AN INVESTIGATION OF THE EFFECTS OF ILLITE CONTENT ON ELECTRO-OSMOSIS

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by 21

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FOREWORD

The author wishes to express his thanks to Professors E.J. Kilcawley and S.V. Best for their guidance and most helpful comments during the course of the investigation.

ABSTRACT

Nine series of tests were made on soil samples composed of Morris, Grundy County, Illinois, illite and Cow Bay, Long Island, N.Y., sand. The ratio of illite to sand was varied in each sample in order to determine the effect which the illite content had on the various factors affected by electro-osmotic treatment. Each sample was pre-loaded to 1/4 T/ft^2, and this load was maintained throughout the test. An electrosmometer was used for this series of tests. The voltage was maintained at a constant value of 2.7 volts giving voltage gradients ranging from 1.36 - 1.56 volt/cm. Nickel-silver electrodes were used.

All the samples in which electro-osmosis was effective had higher values of Atterberg limits after electro-osmotic treatment was completed. Liquid limit, plastic limit and plasticity index all increased as a result of treatment.

A rearrangement of soil particles into three distinct zones was observed in all samples after electro-osmosis had occurred. Concurrent with these three zones was a variation in moisture content between the anode and cathode side of the sample. The overall moisture content was not reduced by electro-osmotic treatment.

For all samples tested with the illite content larger than 20%, electro-osmosis did occur. Values of the electro-osmotic coefficient of permeability were computed, based on initial conditions and on conditions at point of

maximum piezometric rise. In every case the electro-osmotic permeability was much greater than hydraulic permeability. Treatment causes a decrease in hydraulic permeability. Efforts to relate the change in hydraulic permeability and the difference in initial and maximum rise values of electro-osmotic permeability to variations in void ratio were not successful in that no specific relationship was obtained.

pH values for the liquid in the two chambers of the electrosmometer were determined. Change in electrode weights for each test have been tabulated. Value of current flowing has been plotted against time as has the value of piezometric rise.

PART I

INTRODUCTION

Since the beginning of recorded history man has made continual improvements in his material objects to make his life more pleasant and for his very survival in many cases. From the simple shelters, places of assembly, and routes of communication of ancient times the construction industry has moved ever onward with unabated pace. Indeed, in today's world most of us assume that, if something must be constructed at a given location, man's ingenuity will see the job through, no matter how difficult it may be. That this may be done is largely attributable to improvements which have been made in construction materials, to the development of new materials when required, and to new methods of construction. Much of this advance has been due to the fact that man could control his building materials and produce what he wanted for the job in question.

For everything erected by man a foundation has been required to support it, and the soil has provided the ultimate support for all structures. Ironically, soil, the one thing which has been required for all structures has had relatively little attention paid to it. It is the material that man can not take and manufacture in the final desired form. In earlier times it may have been possible to select a site with suitable subsurface foundation conditions for most major structures. If so, this time is gone. With our ever growing

cities, communication routes, dams, etc., it is usually essential that the soil foundations be utilized at some given location without regard to the desirability of same. Hence, we as engineers must make use of what we have and even under the worst conditions erect a useable structure.

It is only in the part 30-40 years that our knowledge of the physical properties of real soil has been accumulated (19). The science of soil mechanics is relatively new, and there are many questions which can not yet be provided with definite answers. However, this information which is now available is a tremendous asset to the engineer who must design foundations and earth structures.

In doing foundation work it is most desirable to work in a dry surrounding under atmospheric conditions. This can be an expensive end to achieve, and in addition it may be a very difficult problem to solve. The very fact that caissons, cofferdams, bulkheads, grouting, freezing, soil solidification, and water removal systems have been employed under various conditions to eliminate the water problem indicates that the problem is complex. However, even such methods as grouting, freezing, chemical solidification, and well point or vacuum pumping are limited to soils which have a certain degree of permeability. Hence, they have been of little or no use in saturated clay soils which are of very low permeability and which flow easily when adjacent clay is removed.

Once again man has had to provide a new process or make use of an existing, unused one to overcome the problem.

In this case it has been the use of electro-osmosis which is basically the movement of water by electrical forces. This phenomenon had been noted in the early 19th century but had not been applied to construction. Electrodes are placed in the soil and a direct current voltage is applied. Water moves from the anode to the cathode where it may be collected and pumped away.

Whereas soil mechanics is a new science, electro-osmosis may be considered as one of its offspring and is newer still. It has been the subject of a considerable amount of study in the past 20-25 years. Much of the study has been sporadic without a continuous plan of research. However, through laboratory experiments and some practical applications it is known that it is possible to change soil properties to our advantage. These changes include: decreasing the water content, increasing bearing capacity, stabilization of slopes, and stabilizing construction excavation. When aluminum electrodes are used electro-osmosis becomes an electrochemical process. The electrochemical action gives a permanent change in soil properties, whereas electro-osmosis alone usually provides only temporary changes.

As with any new tool all interested parties immediately want to know when it can be used and when it can't. Unfortunately, this answer can not be given at this time. The research which has been done provides us with some good indications, however, there are still many factors to be

evaluated. A great deal of work will probably have to be done before electro-osmosis can be reduced to precise facts. There are a multitude of factors which affect the behavior of a clay mass. It is probable that each of these factors affect or is affected by the phenomenon of electro-osmosis.

This study has been undertaken in the hope that something of value, no matter how small in quantity, may be contributed to the enlargement of our knowledge in this particular field. It is also hoped that it will help to keep active a continuing program of electro-osmotic research at Rensselaer Polytechnic Institute.

PART II

HISTORICAL REVIEW

Insofar as practical use is concerned, electro-osmosis is a very new technique, as it is less than 20 years since Casagrande first used it (5). Many papers which have been presented on electro-osmosis have included a section concerning the overall history of the subject from discovery on up to the particular paper. Specifically, studies by Preece (13), Casagrande (6), and Koonce (12) cover the history of the subject and are considered by the author to be essential reading when studying electro-osmosis. Casagrande's review is particularly useful in that he provides additional comments on the individual papers which he has reviewed. Since the reports of Preece and Casagrande are so complete and are readily available, the author does not believe that an extensive duplication of that information is necessary here.

A brief review of some of the findings which have been made and some of the applications which have been made does seem to be in order. Normally in a paper of this type only the particular aspects of the problem which the student is studying are reviewed. As will be evident in THEORY, there are so many factors which are probably all interrelated that no single phenomenon such as permeability or consolidation is being considered. The previous findings which are mentioned in this section are for general information only. The persons who are referenced are in most cases not the only ones who have produced similar findings.

In 1807 Reuss discovered that the application of an electric potential to a porous diaphragm produced a movement of water from the anode to the cathode through the capillaries of the diaphragm. The hypothesis of a "double layer" was formulated by Quincke in 1861. This hypothesis depended on spontaneous electrification existing at the contact surface of a solid and a liquid before any external electrification took place (11). However, it was not until 1879 that Helmholtz tied the phenomenon down by providing a mathematical solution for it. Improvements have been made in his solutions. However, is has remained basically unchanged and provides what is generally accepted as the basis of electro-osmotic flow today.

Casagrande has done a large amount of research in the field of electro-osmosis. He has also been the leader in the practical application of the phenomenon to foundation problems. His experiments led him to apply for a patent (Germany, 1934) on the process of permanently hardening clay soils by using aluminum electrodes (6). He subsequently obtained U.S. and Swiss patents on this process.

After studying some of Casagrande's work, Endell and Hoffman experimented in 1936 with hardening of clays by using aluminum electrodes (9). They found that Atterbergs liquid limit and ϕ were increased and stated that the water content is substantially reduced when a soil is so treated. They concluded that "the process is the first one to attempt to harden clay soils for engineering purposes and the hardening process is on a sound theoretical basis."

In 1939 Casagrande made the first large scale application of electro-osmosis by stabilizing a long railroad cut at Salzgitter, Germany. This stabilization was done as a result of electro-osmosis alone without the hardening influence of aluminum electrodes.

Practically no research was accomplished during the years of World War II. Hence, the majority of the studies have been made since 1946.

Preece published a very interesting and readable paper in 1947 (13). He brought out the point that a physico-chemical knowledge of soils is necessary for a proper evaluation of soil action under various conditions, one of which is that of electro-osmosis. He reported a test which showed substantial decreases in the liquid limit and plasticity index which is the opposite of the findings of Endell and Hoffman. Just to indicate the variables and the complexity of a really complete study of electro-osmosis, it should be noted that Preece proposed to make 23 different tests or analyses before and after each electrical treatment of soil. He also emphasizes the difference in stability achieved by flowing water alone and by flowing water carrying aluminum ions from an aluminum electrode.

In 1948 Bernatzik presented a paper (2) which proposed to show that electro-osmosis does not cause tension in the pore water nor an added compressive stress in the soil. However, Casagrande (5) presents rather elaborate data to

prove just the opposite. It appears that the general consensus of opinion is that there is tension in the pore water.

In 1948 Christensen found that the liquid limit and plasticity index were increased (8). He used aluminum electrodes. He attributed the changes to base exchange and noted that the effects were more pronounced at the cathode. Water poured in at the amode was found to move to the cathode. Cracks developed in the sample. The soil also consolidated a great deal due only to the electrical action.

Geuze, de Buryn, and Joustra made studies of permeability and electro-osmotic head, among other items, and reported on their findings also in 1948 (10). They developed an equation for height of rise or electro-osmotic head and made measurements in an electro-osmometer to check the mathematical results. The head theoretically becomes maximum at an infinite time. Actually the head was found to reach a maximum and then gradually decrease.

Vey (2) in 1949 concluded that electro-osmosis produces an additional consolidation load which is more effective in producing consolidation when the soil is under an applied load.

Spangler and King tested the bearing capacity of clays soils by using small aluminum coated piles as the electrodes (17). They found that after a certain amount of treatment the bearing capacity was greatly increased. However, further treatment showed a marked reduction which was

believed to be caused by a decrease in skin friction. They also showed a higher bearing capacity was produced when the percentage of clay sizes, 2 microns, was increased.

An important factor in practical application of electro-osmosis is pointed out in Casagrande's paper of 1952 (5). This is that a very small decrease in moisture content is sufficient to produce the required stability in many cases. He further indicates that electro-osmosis would not normally be an economical method of decreasing the moisture content to any considerable extent.

Shukla's studies in 1953 (16) showed, after treatment,"a decrease of plasticity and an increase of shear strength, permeability, compressibility, compaction density and structure depending on the mineralogical composition." He noted a marked reduction in liquid limit but not in plastic limit. He found aluminum hydroxide precipitated in the soil and presumed that it acted as a soil binder similar to calcium carbonate.

Butler (3) and Tarran (18) reached some identical conclusions in their studies in 1955. They reported a definite increase in consolidation, increases in Atterbergs limits, and substantial decreases in moisture content. Tarran noted that electro-osmosis decreased the time for complete consolidation for the smaller load increments but had either no noticeable effect or caused an increase in time for the larger load increments. He also found that the coefficient of con-

solidation was affected to a larger degree at the lower load increments.

From the above outline it can be readily seen that various and conflicting results have been obtained from electro-osmotic research. Some of the possible reasons for this will be brought out in THEORY immediately following this section.

PART III

THEORY

A. Introduction

From the historical review it is seen that there has been a large variance in the results obtained from electro-osmosis. Many researchers put forth their own theory to explain a particular result. However, it is impracticable to try to cover all of the theories in this paper.

In the sections which follow the basic Helmholtz equation for electro-osmotic flow will be discussed. Since the primary use of the electrosmometer is to determine permeability relationships, the theory of this relationship will be presented. Also, some of the theory concerning clay soils will be outlined, because of the importance of electro-osmosis in stabilizing clay soils.

The reader is referred to the work of Preece (13) which gives a very good presentation of many of the factors involved in electro-osmotic treatment of clays.

B. Basic Concepts Of The Electro-Osmotic Phenomenon

There are certain terms which are associated with electro-osmosis and which should be defined. Many people have an idea of what osmosis is and think that electro-osmosis is a similar phenomenon. That they are different will be evident from the following definitions. If two solutions of different concentration are separated by a suitable semi-permeable membrane, the molecules of the solvent, but not those of the

solute, will tend to pass through the membrane from the solution of the lower to that of the higher concentration. This is called osmosis (13).

(i) Electro-osmosis - movement of the liquid relative to the solid due to an externally applied EMF.

(ii) Streaming potential - an EMF produced by movement of the liquid with respect to the solid due to hydrostatic pressure.

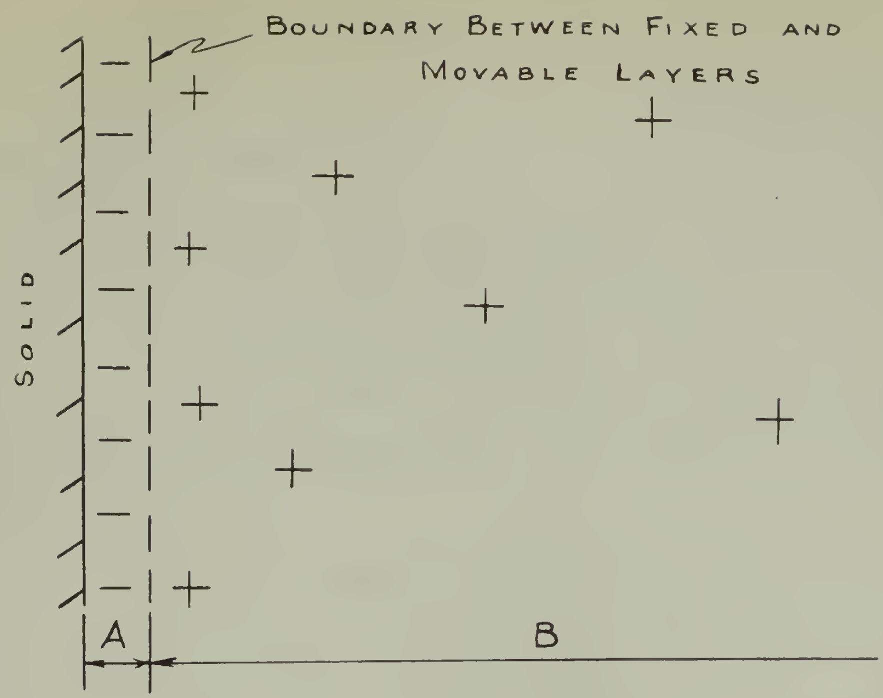
(iii) Electrophoresis - movement of the solid with respect to the liquid due to an externally applied EMF.

(iv) Migration potential - an EMF produced by the movement of solid particles relative to the liquid (such as occurs during sedimentation).

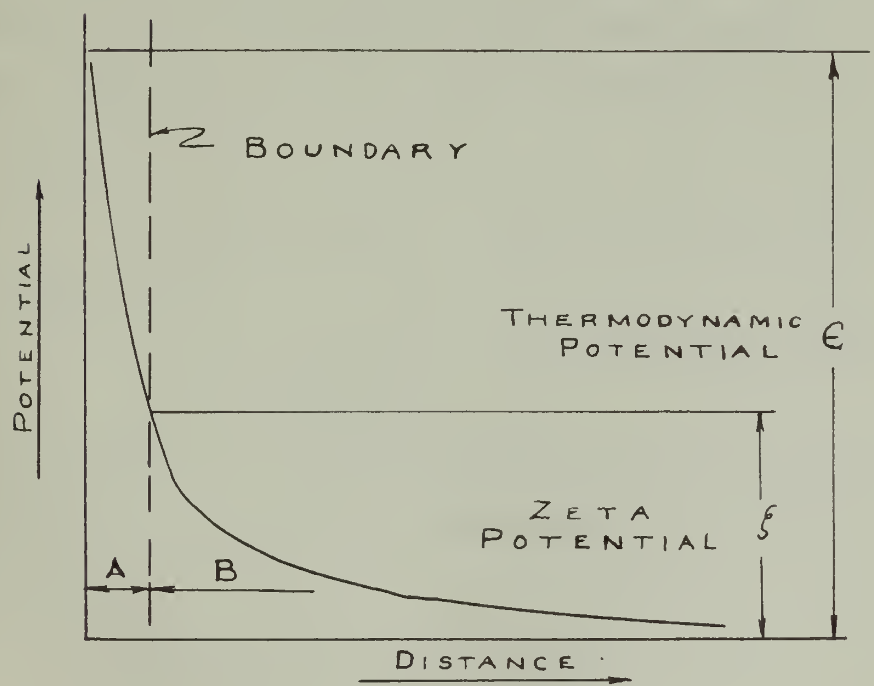
(v) Double layer - the arrangement of ions in the liquid adjacent to the solid such that two distinct layers of opposite electrical charge exist. See Figure I. Adjacent to the solid is a very thin layer of immovable ions, and adjacent to this layer there is a counter layer of varying thickness. Any movement of water therefore stops at the boundary between the two layers.

(vi) Zeta potential (ζ) - that part of the total potential difference which exists between the boundary separating the two layers and the outer limit of the diffuse or movable layer, see Figure II.

Helmholtz visualized the double layer as a condenser with the negative plate being the fixed layer and the positive plate the difuse layer, the two being parallel and separated by a very small distance. Applying condenser principles he was able to solve mathematically for the zeta potential. His equation has been improved upon, and from the improved equation the quantity of liquid moved in a unit time by electro-osmosis in a single capillary can be computed as:



Double Layer
Figure I



Zeta Potential

Figure II

$$(1) \quad q_e = \frac{E\,D\,r^2\,Z}{4\,n\,L}$$

where all dimensions are in cm - g - sec system and electrostatic units, and

E - the electric potential
D - the dielectric constant of the liquid
r - the radius of the capillary
Z - the zeta potential
n - the viscosity of the liquid
L - the length of capillary between electrodes

A more detailed development of the Helmholtz equation is given by Vey (20).

The above equation can be made analogous to the hydraulic flow equations by a simple procedure (5). Let $\frac{E}{L} = i_e$, the potential gradient, $\frac{D\,z}{4\pi n} = c$, a constant (this can be done because most soil liquids have a zeta potential which is relatively constant and equal for the various soils (5) , and $r^2\pi = a$, the cross-sectional area of the capillary. We then obtain:

$$(2) \quad \begin{aligned} q_e &= c \quad i_e \, a \\ V_e &= c \quad i_e \end{aligned} \qquad \text{for electro-osmotic flow}$$

as compared to:

$$(3) \quad \begin{aligned} q_h &= c_2 \, i_h \, a^2 \\ V_h &= c_2 \, i_h \, a \end{aligned} \qquad \text{for hydraulic, laminar flow.}$$

For a group of N straight capillaries in the total cross-sectional area A, with a void ratio e, the rate of hydraulic flow is:

$$(4) \quad \begin{aligned} Q_h &= N \, q_h = (a \, \frac{e}{1+e} \, c_2) \, i_h \, A \\ &= K_h \, i_h \, A \end{aligned}$$

and the corresponding rate of electro-osmotic flow would be:

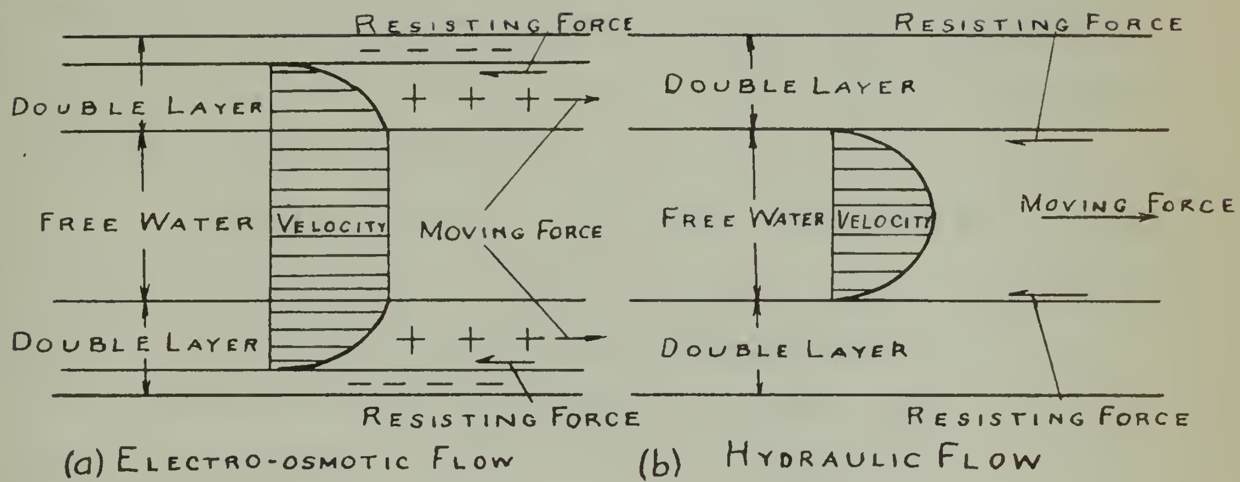
$$(5) \quad Q_e = N\, q_e = \left(\frac{e}{1+e}\; c\right) i_e\, A = k_e\, i_e\, A$$

Equations (4) and (5) point up the very important difference between hydraulic and electro-osmotic flow, namely that the coefficient k_e and the rate of electro-osmotic flow are independent of the size of the capillaries. Since the small pore sizes of clay soils make it impossible to drain the soil by hyrdaulic flow, the possibilities of using electro-osmosis are readily apparent. A diagrametric comparison of electro-osmotic flow with hydraulic flow in a single capillary is shown in Figure III. It must be kept in mind that the equations and flow conditions are based on idealized conditions which do not exist in clays. For example the pores are not straight capillaries, the void ratio is not constant during electro-osmosis, and pore sizes are not uniform throughout the sample. However, this does not detract from the usefulness of the theory for visualizing what happens.

From the Helmholtz equation the hydrostatic pressure which builds up at the cathode is:

$$(6) \quad P = \frac{2\, z \quad E\, D}{\pi\, r^2}$$

Since the values needed to compute P directly are difficult to determine, other methods are used to find it. Casagrande (4) determined theoretical and actual values for various types of soils with widely varying pore sizes. His values were in good agreement as long as the soil did not contain colloidal particles. For colloidal material the pressure developed



Comparison of Electro-osmotic Flow With Hydraulic Flow in a Single Capillary

Figure III

corresponded to much coarser material. Casagrande noted that under electro-osmotic treatment all soils containing colloidal particles fissured. He then made the supposition that flow was primarily in the fissures and not in the pores per the Helmholtz theory. Vey (20) noticed the same sort of results. However, he believed that electro-osmotic flow continued in the pores but that hydraulic flow in the opposite direction through the fissures tended to balance the flow.

Geuze, de Bruyn, and Joustra (10) attacked the problem of determining the coefficient of permeability k_e and the head due to electro-osmotic forces through the use of an electrosmometer. The application of an EMF causes water to rise in a piezometer tube located just back of the cathode. They developed an equation based on differential flow:

$$(7) \quad \frac{dh}{dt} = \frac{(k_e U - k h)\, O}{F d}$$

where

- h - height of rise above the constant level at time t after the start of the test
- F - cross sectional area of piezometer tube
- O - cross sectional area of sample
- k_e - electro-osmotic coefficient of permeability
- k - hydraulic coefficient of permeability
- U - electrical potential between electrodes in volts
- d - distance between electrodes

The solution of equation (7) gives:

$$(8) \quad k_e = \frac{k h}{U} \; \frac{e^{\frac{k O t}{Fd}}}{\left(e^{\frac{k O t}{Fd}} - 1\right)}$$

or

$$(9) \quad h = \frac{k_e U}{k} \; \frac{\left(e^{\frac{k O t}{Fd}} - 1\right)}{e^{\frac{k O t}{Fd}}}$$

The maximum height of rise will occur when $\frac{d\,h}{d\,t}$ is zero in (7) above. Solving:

$$(10) \quad h_{max.} = \frac{k_o}{k} U$$

This condition theoretically exists when t becomes infinite in equation (9). However, in actual testing the rise is found to reach a maximum and then to decrease from the maximum with continued treatment.

The decrease in k_o was attributed to the action of the electrodes whereby:

> "(a) The anode cupric-ions went into solution and had a strong flocculating power on the negatively charged soil particles.
> (b) The cathode cupri-ions may cause the formation of insoluble copper compounds."

The value of k also decreased, and this was also believed to be indirectly due to the same electrode effects. Casagrande (6) experienced the same type of results, but he was using platinum electrodes. He attributes the decrease to the decrease in void ratio brought about by consolidation. The void ratio decrease will lower the values of both k_o and k.

Schaad (15) points out that there are several factors affecting electro-osmosis which the Helmholtz equation does not take into account. These factors include electrolysis of the water, current flow through the soil particles, inversion and oscillation of flow, and changes in the concentration of the electrolyte. These factors are more pronounced in long-time laboratory tests and are not too noticeable in field applications where a rather steady flow may be

observed for several days. He believes that the results from the first part of test procedures are more representative of field conditions. To express this condition mathematically he differentiated equation (9) with respect to time and ended up with the following expression of k_e at the very start of the test:

$$(11) \quad k_e = \frac{F}{OE} \tan \alpha_o$$

where k_e, F, and O are as previously defined, E is the potential gradient $\frac{U}{d}$, and α_o is the angle between the tangent to the height of rise vs time curve and the horizontal at zero time. This value of k_e is independent of k. However, Butler (3) obtained exceptionally close agreement between equation (11) and equation (8).

Although there are many other ideas and personal theories or beliefs concerning various individual tests which have been run, as well as some other mathematical theories, the above is believed to be an adequate review for this set of tests. Additional data presented in sub-section C below will more nearly round out the theory of electro-osmotic flow.

C. <u>Clay Soil Factors In Electro-Osmosis</u>

Electro-osmosis can not be considered as simply the movement of water through pores of an inert solid. This has been recognized by many researchers. Winterkorn (21) states, "The central problem with respect to the engineering treatment of soils concerns their water relationships." Vey (20) says,

"The phenomenon of electro-osmosis is fundamentally a phenomenon of colloid and capillary chemistry."

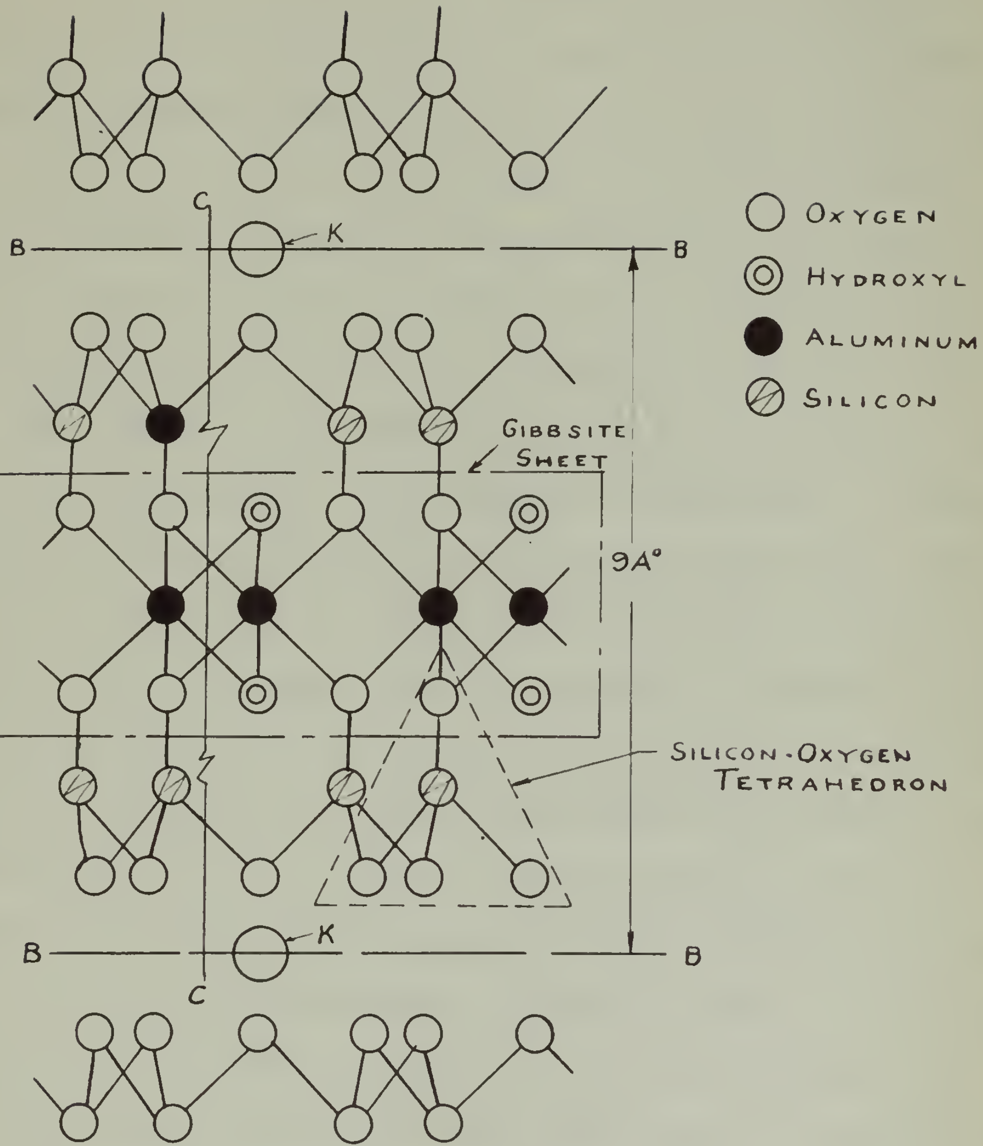
"Clays are disperse systems of the colloidal products of weathering in which secondary mineral particles of smaller dimensions than 2 microns predominate" (1). Clays are constituted of distinctly crystalline minerals which are in turn built up of units of alumina and silica. A crystal is a three-dimensional repitition of unit cells, the structural arrangement of which is called a space lattice. For clays the unit cells are the silicon - oxygen tetrahedron and the aluminum - hydroxyl octahedron which when banded together by electrostatic forces produce the elementary lattice structures called the tetrahedral silicon sheet and the gibbsite sheet respectively. The arrangement of these sheets to form the clay mineral illite is shown in Figure IV. This is a 2 : 1 lattice with adjacent lattices bound closely together by potassium atoms located on the basal cleavage plane B-B. Also, some of the silicon atoms may be replaced by aluminum atoms, and some of the aluminum atoms may be replaced by iron or magnesium.

It can be seen that the lattice, if it were continuous to an infinite length, would be electrically neutral, as there would be no unsatisfied valences. However, the particles are small, and breakage along the plane C-C gives rise to unsatisfied valences. These unsatisfied valences cause the clay to be classed as active material. Since clay particles

are so small, there will be a very great number of unsatisfied valences per unit volume of solids, thereby causing the clay to be a very active material. The clay tends to satisfy this electrical unbalance by adsorbing ions from the surrounding solution. "Nature always tends to produce matter having the smallest possible amount of free surface energy, and of two possible combinations, that producing the least soluble compound will have the least free energy. Adsorption of ions by a solid from a solution is, therefore, a preferential process" (13). The clay preferentially adsorbs a layer of negative ions which themselves attract a counter layer of positive ions producing the double layer.

The thickness of the double layer and the force with which it is held to the solid are dependent on the size of the ions. Since the ions are in water, the size of the hydrated ions is the size which must be considered. The original solution may be replaced or different ions may be introduced to change the solution. If the new solution will result in a decrease in the degree of hydration or in a lower net charge the new ions may replace the ions of the original double layer either in part or in whole. This is called base exchange (13).

The zeta potential depends quantitatively upon the thickness of the adsorbed layer, the thickness of the diffuse layer, and the total potential. The total potential depends, in turn upon the character of the solid and the solution within



Illite Space Lattice

Figure IV

which it is in contact. Considering these facts and the clay factors outlined above, it is readily apparent as to why clay and electro-osmosis go hand in hand.

It is desirable to briefly consider another aspect of clay, and that is the association of water films with the strength characteristics of clay. "Soil consistency is usually defined as a term to designate the manifestations of the physical forces of cohesion and adhesion acting within the soil at various moisture contents" (1). Moisture is adsorbed upon the surface of the clay as previously outlined. The force with which particles are attracted to one another will depend inversely upon the thickness of the films. Cohesion depends upon the summation of individual film forces and hence upon the total number of films. "Consequently, maximum cohesion is obtained at that moisture content at which a moisture film is established at all points of contact. As the thickness of the moisture film increases beyond this limit, cohesion decreases" (1). Maximum cohesion should result when the moisture content is at the plastic limit. Since clay in nature is normally at a moisture content in excess of the plastic limit, a reduction in moisture by base exchange or by simply removing some of the water would tend to increase the strength characteristics of the clay.

Considering all of the factors brought out, it can be stated that clays are particularly adapted for electro-osmotic treatment.

PART IV

MATERIALS AND APPARATUS

A. Introduction

The primary requisite for undertaking this experiment, as far as equipment was concerned, was an electrosmometer. Fortunately, this device was available in the Civil Engineering Department. If had been constructed and used by Tarran (18) and Bulter (3). Its design is such that it can also be used as a falling head permeameter by simply raising the water level in the piezometer tube and letting the water flow out through the overflow on the opposite side. This arrangement is very convenient. It permits the natural permeability to be determined after the electrical test is completed. In addition it is not necessary to prepare a separate sample for permeability testing. Some variations were made in the electrosmometer and are described in detail further on in this section.

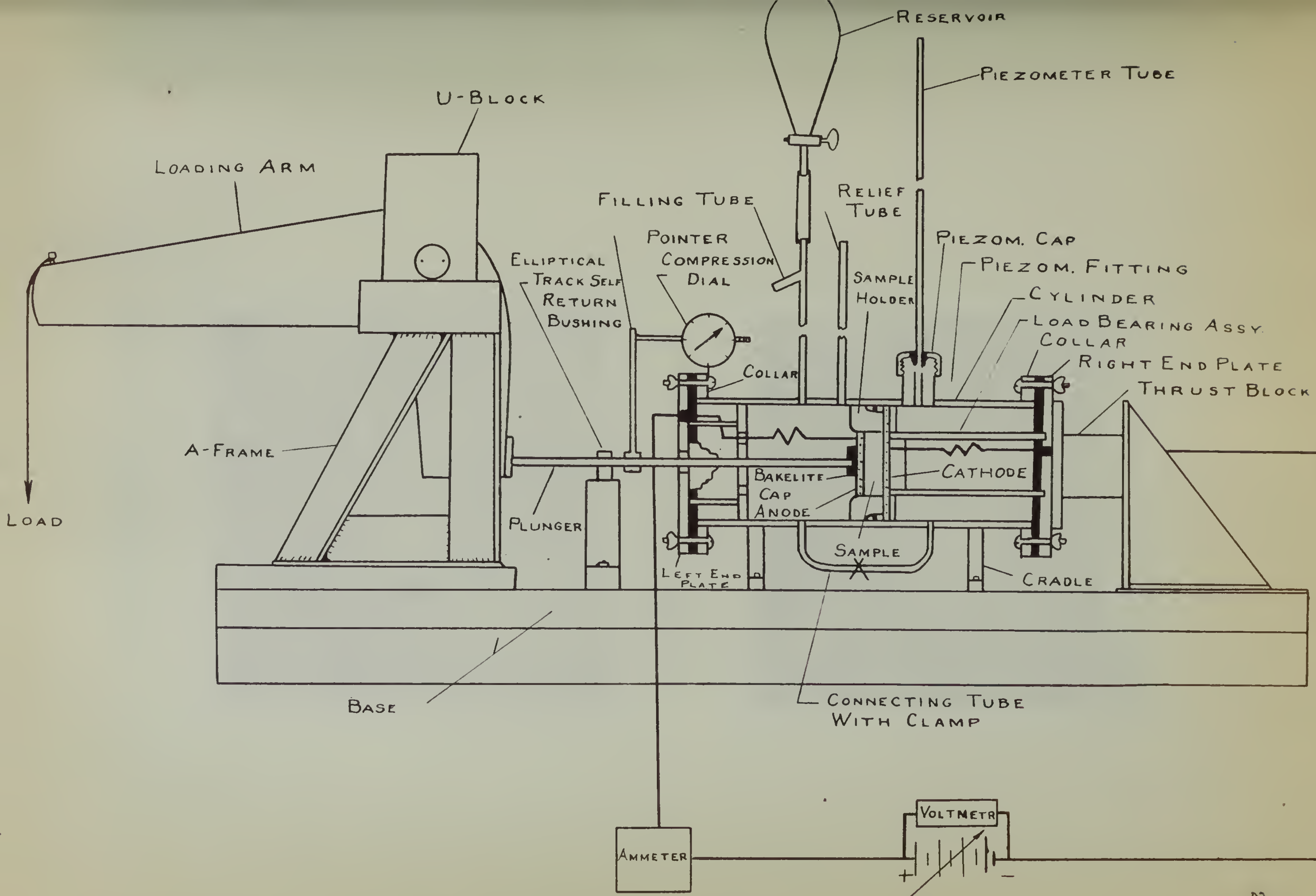
The author was also fortunate in having a variable source of D.C. power available. This permitted the electrical gradient to be maintained at a value which is believed to be comparable to values which can be obtained in the field. Voltage was measured by use of a single-range D.C. voltmeter and current by a three-range D.C. milli-ammeter. As discussed later on no attempt was made to use a thermocouple to measure temperature changes in the sample.

B. The Electrosmometer

A complete discussion of the design and construction of the electrosmometer is given by both Tarran (18) and Butler (3). Therefore, it is not deemed essential that such a detailed description of it be presented here. A general description of it will be given. This, together with an explanation of changes made and an examination of the schematic drawing and the photographs will enable the reader to fully understand the apparatus. Figure V is a schematic diagram of the electro-osmometer and its electrical components. Figure VI and Figure VII show the electrosmometer in use.

The main body of the electrosmometer is a 4.0" I.D. lucite tube 13" long. 7" square collars with a 4.5" cutout are bonded on each end and drilled for 8 bolts which are used for securing the end plates which sandwiches the rubber gaskets between for water tightness. A lucite sample holder fits inside the lucite tube and is about 1 1/8" thick. It has a hole 2.505" in diameter cut through it to hold the sample. The outside of the holder had a rough-faced, tapered cut about 0.7" long made on it so that a 4" O.D., 3 3/4" I.D. rubber "O" ring could be placed thereon to seal off the flow of water between adjacent sections of the osmometer except through the sample.

Various loads can be applied to the sample by changing the weight suspended from the loading arm. This load is transmitted to the sample through a stainless steel plunger



Schematic Diagram of Electrosmometer
Figure V

Figure VI Full View of Electrosmometer

Figure VII Angular View of Electrosmometer

which bears against the anode. The anode fits closely inside the sample holder and provides a uniform transmission of the load to the sample. The load is further transmitted to the cathode which is placed against the other end of the sample holder. The cathode in turn is backed up by a load bearing assembly which transmits the load to the end plate which in turn is backed up by a thrust block. The thrust block is securely bolted to the base so that there can be no movement, except for expansion or contraction of the sample. An elliptical track, self return bushing is located between the loading assembly and the lucite tube to take any vertical components of thrust from the plunger. Figure VIII shows the parts of the main body of the electrosmometer.

A tube on the bottom connects the spaces on the anode and the cathode sides so that the entire body can be uniformly filled. The relief tube and filling tube are made of rigid vinyl bonded into the top of the tube. A threaded fitting is provided for the piezometer tube so that it may be quickly and easily removed from the electrosmometer. The piezometer tube is glass, and the one used in this experiment had a cross section of .4395 cm^2.

The electrodes, a 2.5" diameter anode and a 4.0" diameter cathode, used were composed of nickel silver, fine grade. The wires from the power supply were soldered to the electrodes. Lead-in wires were permanently fixed in the respective end plate by passing them through rubber stoppers and

Figure VIII Parts of Electrosmometer

Left to right:

(a) Sample holder
(b) Left end plate with plunger and anode
(c) Main cylinder
(d) Load bearing assembly
(e) Right end plate with cathode

forcing the stoppers into a tight fit in holes drilled in the end plates.

The entire assembly is mounted on a heavy plywood base which in turn is mounted on two 2"x2"x3/16"x4'-6" angles running the length of the base. Both the thrust block and the support for the elliptical track self return bushing are held in place by vertical bolts which pass upward through the base.

Certain changes were desired to make the equipment somewhat more versatile and/or easy to use. Since anode decomposition starts as soon as the current starts to flow, it was desired to record the weight of the anode and also the cathode prior to and after each test. This was easily accomplished by cutting the leads to the two electrodes and placing a plug and jack connection in the circuit. Banana plugs were connected by means of a set screw in the plug to the wire connecting with the electrode. A banana jack was soldered to each wire leading to the power supply, The plug fits into the jack and makes a satisfactory connection.

Both previous users of the equipment (18,3) indicated difficulty in getting a tight seal between the collars and end plates. 1/4" "O" rings were previously used. These had to be carefully placed for each experiment. This difficulty was eliminated by making some gaskets of 1/8" sheet rubber. The gaskets were cut 7"x7" to fit the end plates. The hole in the center of each gasket was cut somewhat smaller

than the 4" I.D. of the electrosmometer to prevent any of the bubbles which formed from becoming locked in. Testing under a relatively high static head showed that no leaks developed.

The inner end of the load bearing assembly comes to rest under the piezometer fitting. Consequently, there is a large notch in the top of the bearing assembly to permit air and other gases to escape. The shaft of the bearing assembly has several large holes in it to permit bubbles which form within it to reach the surface. However, with the notch placed on top as required, none of the holes in the bearing assembly were located at the top. It was necessary to drill additional holes in the top and bottom to release the gases which were developed.

Raising the entire assembly by placing 2" x 4" planks longitudinally under the angles supporting the base made it immeasureably easier to tighten the thrust block and the self return bushing assembly. Prior to raising it was next to impossible to reach under the base and tighten them while working alone.

An attempt was made to connect an aspirator to the electrosmometer to de-air the water prior to testing. However, it was found that the amount of vacuum required to remove the air also removed some of the water. Hence, only regular distilled water was used.

One small calibration was required to permit direct reading of the sample thickness during the tests. A circular

carbon disk .372 in. thick was placed in the sample holder just as if it were a soil sample. It was covered on each end with filter paper and then placed in the electrosmometer which was then assembled for testing. With a load applied to give 1/4 T/ft^2 on the disk, the brass pointer was placed at a marked point on the plunger and the compression dial read. With this reading known, it was possible to determine the sample thickness, since the pointer was always placed at the same location.

C. Electrical Components

A portable power unit which had been recently obtained by the Civil Engineering Department was made available to the author. It is more versatile, much lighter in weight, and cleaner than the battery source previously used (18, 3). The unit is the Fisher Powerhouse No. 9-518 manufactured by the Fisher Scientific Company. The unit, when attached to a 115 - volt 50/60 - cycle line, becomes a source of continuously variable direct or alternating current. A built-in dry disc rectifier and filter is used as the direct current source. The D.C. voltage varies from 0-10 volts and is controlled by a large dial on the front. It has a maximum current rating of 10 amperes. However, the current required in the various tests was measured in milli-amperes. At maximum current output the unit has less than 5% ripple. There are slight variations in the voltage output which are caused by variations in the A.C. supply. However, the variations are no larger than

about .05 volt which is of no importance in the effect it has on electro-osmosis.

Although there was a voltmeter on the power unit, it could not be read with suitable accuracy. Therefore, a single range, 0-5 volts, D.C. voltmeter, Weston Model 301 was used. It had 0.1 volt divisions on the scale and was satisfactory in all respects.

The ammeter on the power unit did not record the current, because it was of such small magnitude. Consequently, a separate meter was required. It was a Weston Mil-Ammeter, Model 269, No. 15184 with three ranges: 0-15, 0-75, and 0-300 milli-amperes. Only the two lower ranges were required.

The author considered using a thermo-couple to record any temperature changes within the sample during electrical testing. A study of the results obtained by Tarran (18) and Butler (3) indicated that this would be wasted effort. They obtained a maximum temperature difference of plus 5° C for a brief time, and the majority of the time there was no difference. Since the author's series of tests utilized an even smaller applied voltage with subsequently smaller current, it was assumed that temperature differences would be so small as to be negligible.

The wires used for all electrical connections were a standard 6 conductor, rubber insulated type. The wires were connected to the anode and cathode by simply soldering

them to the external faces. After the banana plugs and jacks were installed the exposed metal surfaces were coated with vaseline. This was done to prevent current leakage, electrolytic action on the metal itself, and rust accumulation in the water.

PART V

PROCEDURE

A. Sample Characteristics

As indicated in THEORY and HISTORY the phenomenon of electro-osmosis is not yet understood to the degree that will allow an engineer to know whether it can or can not be successfully applied to a given soil deposit. Many factors, such as type of clay, mineralogical and chemical nature, particle size, and other material present, to mention only a few, affect the behavior of clay. These factors then will have varying effects on the electro-osmotic phenomenon. Therefore, it seems essential that any study of electro-osmosis must of necessity present as much information as possible concerning the characteristics of the soil. One of the defects noted in the review of previous studies by Casagrande (6) was the lack of this information. "There is a lack of reporting of vital data which are necessary for proper interpretation of the results, as e.g. the results of classification tests on the soils used." The purpose of this section is to present the data concerning characteristics of the soil as originally received and to indicate characteristics which changed with each sample tested.

The soil samples tested were composed of illite and fine grained sand passing a number 40 sieve. The general chemical composition of illite is:

$$(OH)_4\ K_y\ (Al_4\ Fe_4\ Mg_6)\ (Si_{8-y} - Al_y)\ O_{20}$$

The American Petroleum Institute (14) reports that the illite used occurs in a clay pit of the Illinois Clay Products Company in the Goose Lake area, about seven miles east of Morris in Grundy County, Illinois. It is approximately 90% pure illite with the following impurities: 2% quartz, 2% sericite, 2% limonite, 2% plagioclase, about 3% pyrite and a trace of carbonate.

X-ray analysis and differential thermal analysis (18) showed that the illite content was about 90% and that no kaolinite or montmorillonite were present. The differential thermal analysis did show that a small amount of organic matter was present.

The Atterberg limits of the illite are: liquid limit 56.6, plastic limit 29.6, and the plasticity index 27.0.

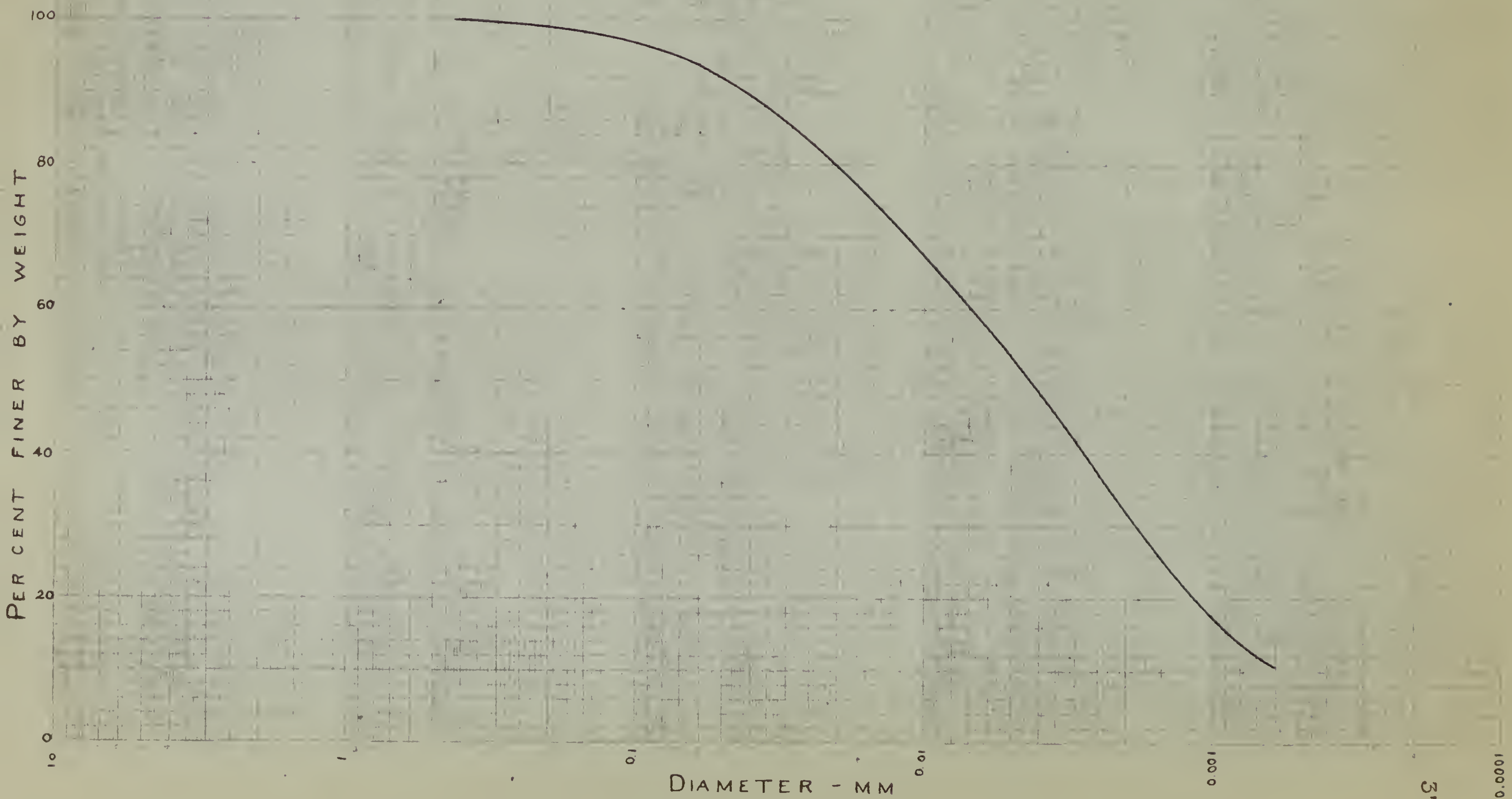
Specific gravity is 2.76.

The soil as received is in a powdered form and needs no preparation prior to use. The grain size distribution curve is shown in Figure IX, and it can be seen that 95% of the material passes a number 200 sieve.

The sand was obtained from a local building supply company. It was prepared for use by sieving out the coarse particles and retaining only those passing the number 40 sieve. The sand is obtained from Cow Bay, Long Island, and is appropriately termed Cow Bay Sand. The minus 40 particles used in this study were approximately 90% angular quartz, about 9% of dark rock fragments believed to be of ferro-magnesium compo-

GRAIN SIZE DISTRIBUTION CURVE
FOR ILLITE USED IN TESTS

FIGURE IX



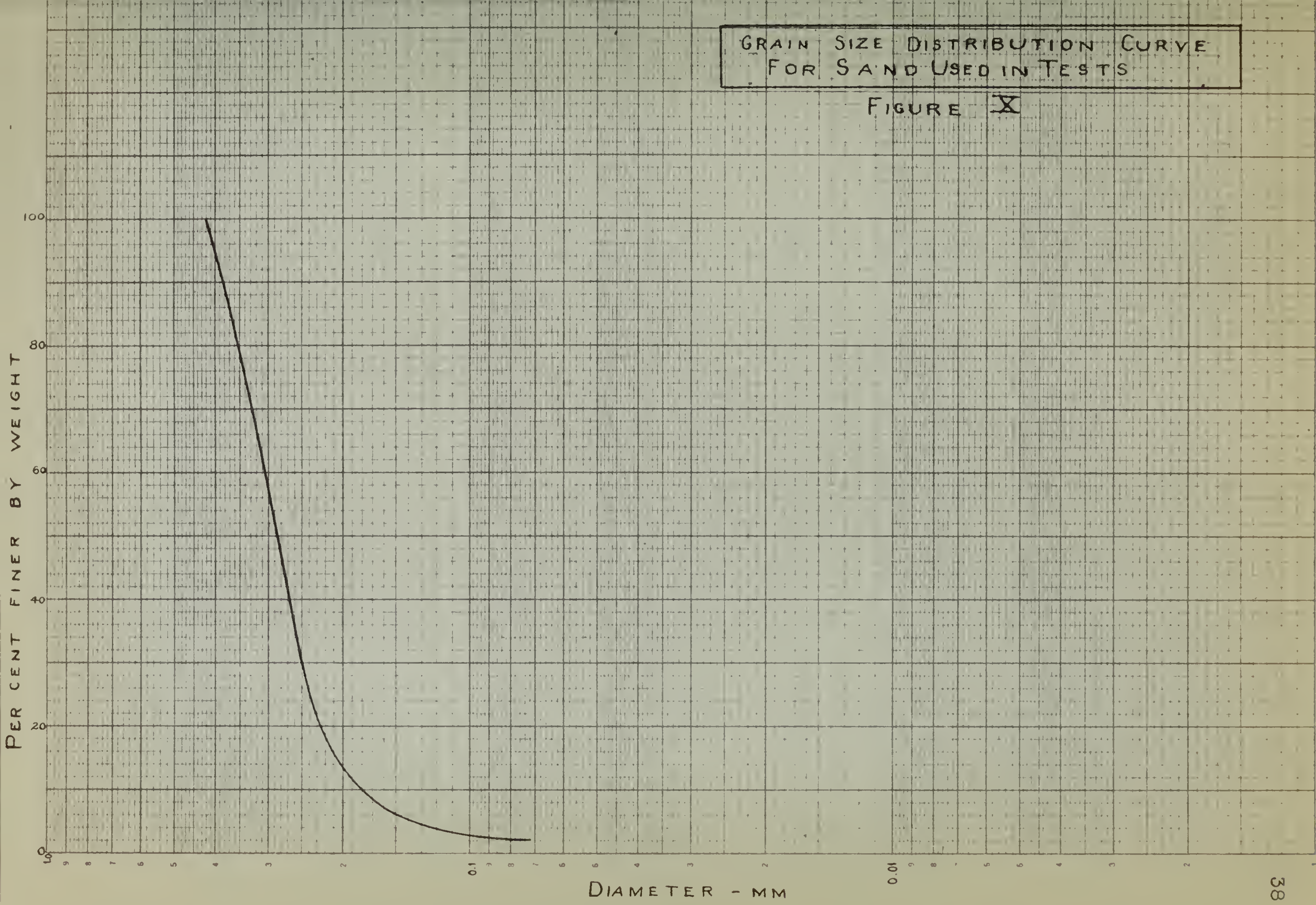

GRAIN SIZE DISTRIBUTION CURVE
FOR SAND USED IN TESTS
PER CENT FINER BY WEIGHT
100
80
60
40
20
0
DIAMETER - MM
0.1
0.01

FIGURE X

sition, and a small amount of white mica and schist.

The specific gravity of the sand particles used was determined to be 2.72.

The sand as received had been washed and was judged to be clean enough to use without further washing. The grain size distribution curve is shown in Figure X. There is an overlap of grain sizes with the illite.

Atterberg limits were obtained for each sample prior to testing and at the conclusion of the test. Void ratio was determined at the beginning of each test. Natural permeability was determined prior to and subsequent to electrical testing.

B. Sample Preparation

In order for the effect of illite content to be the only dominant factor in the results obtained, it was necessary that all samples be prepared under as nearly identical conditions as possible. Also, it was desired that the tests be run under identical conditions of loading and electrical gradient.

It was decided that the sample should be under some small load while electro-osmosis was taking place. Since some load is naturally applied in keeping the sample properly seated in the electrosmometer, enough additional load was applied to provide 1/4 T/ft^2. However, to prevent any consolidation from occurring other than as a result of electrical forces, the soil was preloaded to this value.

Representative samples of illite and sand were taken for each sample tested. They were mixed by weight to give the desired illite content. The sand and illite were added in small amounts and thoroughly dry mixed. After dry mixing enough water was added to bring the sample approximately to its liquid limit. It was mixed by hand until all material appeared moist after which it was further mixed for several minutes by an electrical, household type mixer. Next the material was preloaded, Figure XI. This was done by placing the soil in a $2\frac{1}{2}$" I.D. lucite tube in relatively thin lifts. Porous stones covered with filter paper were placed on top and bottom of the material. The sample was then loaded for a period of from 4 to 6 days with both top and bottom stones supplied with water to prevent drying of the sample. The procedure resulted in samples which were practically free of air voids and in which the illite is believed to be adequately hydrated.

A portion of the sample was placed in an air tight jar and allowed to set for at least 24 hours. This sample was used for obtaining the original Atterberg limits. Allowing the material to set resulted in a more uniform distribution of moisture and permitted hydration of the clay to take place before determining the limits.

C. Assembly Of Apparatus And Sample

The soil was pushed from the pre-consolidation tube directly into the sample holder. In order to get a known

Figure XI Preloading of Sample

thickness of sample and an identical thickness for each test the previously mentioned carbon disk was placed in the anode side of the holder. The soil was then pushed in until firm contact was made with the disk. A wire type cutter was used to cut the sample flush with the cathode face of the holder. A filter paper and glass plate were placed over the exposed soil to prevent loss of moisture until the sample was weighed.

After weighing the sample the glass plates and carbon disk were removed, and the sample holder was inserted into the electrosmometer. This was a rather difficult procedure and was carefully handled. It was found that the small rubber "O" ring would stay on the small end of the sample holder while it was being inserted. The holder was inserted at the cathode end and slowly pushed into position, making use of a large rubber stopper on a metal rod as a pusher to apply even pressure to prevent binding. When the proper position was reached, the pusher was placed in at the anode end, and the sample holder was then pushed toward the cathode until the "O" ring became firmly seated. At this point the holder was slightly past its final required position. A filter paper was placed over the exposed soil and the cathode placed in position. The bearing assembly was then inserted and the right end plate bolted into position. When the bolts were tightened the sample holder was automatically pushed toward the anode and assumed its correct position with the cathode bearing firmly against the sample.

The electrosmometer body was then turned on end with the anode side up. The soil was covered with a filter paper, and the anode was placed in position. The plunger was set against the anode, and the left end plate was bolted onto the left collar.

The electrosmometer was then placed on the cradle, the self return bushing placed on the plunger, and the osmometer filled with water. After getting the entrapped air out as best as could be done, the thrust block was brought to bear and bolted down, and the load was applied. The piezometer tube was installed, the water reservoir connected, and the electrical leads connected to make the equipment ready for the actual test.

D. Testing Procedure

The original Atterbergs limits were determined prior to placing the sample in the electrosmometer.

When the sample was originally cut off a small sample of soil from the unused portion of the mix was taken for the determination of initial moisture content.

After placing the sample in the electrosmometer and applying the load, it was left standing until there was no further movement indicated by the compression dial. This was necessary for two reasons. First, the sample may not have been fully consolidated due to its thickness, particularly for the samples with high clay content. Second, there was

certain to be some rebound during the time that the sample was not under load.

After consolidation was complete the piezometer tube was filled until the level was 25-30 in. above the constant head in the filling tube. The initial permeability of the sample was then determined after the water had fallen for a suitable length of time, generally 3-4 hours. The head on both sides of the electrosmometer was then equalized by opening the bottom connecting tube.

With the heads equal the bottom tube was clamped shut again, and the power turned on. A potential of 1.5 volts per cm was maintained throughout the test. Current flowing, height of rise in the piezometer tube, compression dial reading, and time were recorded until the height of rise was definitely past its maximum value. Accurate values for height of rise were rather difficult to obtain due to bubbles of gas which formed at the cathode. These bubbles were particularly troublesome in that they formed on the cross pieces of the bearing assembly and did not come free of their own accord until they became quite large. However, by gently tilting the base of the electrosmometer and by squeezing on the bottom connecting tube enough to agitate the water, it was possible to dislodge a large part of the gas just prior to making a reading.

When the rise was definitely past its peak value, the power was turned off, and the current and EMF induced into

the soil was determined by reversing the ammeter leads.

The piezometer tube was filled again, and the permeability of the sample determined again. The heads were again equalized.

The water was removed from the electrosmometer. This was done without opening the bottom tube in order that samples of water from both the cathode chamber and the anode chamber could be collected without mixing. Of course, when the heads were equalized, some of the cathode water passed into the anode space. The water samples were tested for pH value by using a pH meter.

After drainage was complete the sample was removed from the electrosmometer. Small samples were immediately taken from the cathode face, the anode face and the middle of the sample for moisture content determinations. A small section of the sample was set aside for observance after it dried. The remainder had water added to it, was thoroughly mixed up to break up the structure which had formed and then placed in an air-tight jar for at least a day, after which Atterbergs limits were again determined. This completed the testing procedure for each sample.

PART VI

RESULTS AND DISCUSSION

A. General

The purpose of this section is to state the results of the tests as observed by the author and to discuss the results as thoroughly as possible. Due to variations in material and equipment used and due to incomplete information of the exact procedure used by other investigators, it is rather difficult to correlate the results obtained with the results obtained by them. However, where basic similarities or obvious differences exist, discussion is made of the similarity or difference.

Since the test results follow a general pattern for all tests, this general section will include those results which seem to hold most uniformly for all samples tested. This will save a lot of needless repitition which would result if each sample tested were discussed separately. Variation of a particular result for an individual sample is also covered in the general section. Due to extreme variations in results, the 90% illite, 10% sand, the 20% illite, 80% sand and the 60% illite, 40% sand (a) samples are briefly discussed in separate subsections.

To save time and space the samples are referred to by percentages of illite and sand respectively. In other words 70/30 means 70% illite and 30% sand; the first number in all cases is the percentage of illite. The word "treatment"

as used hereinafter refers to application of the electrical potential to the sample so that electro-osmosis occurs.

Table 1 is a compilation of most of the results obtained during this study. This table and the graphs which are included for some specific results make a relatively complete picture of all the results. Raw data for each sample tested is tabulated in Appendix A. Sample computations appear in Appendix B.

Physical Appearance

When the sample was removed after treatment the cathode face was found to be quite brittle. It had a tendency to flake off when a small sample was removed with a spatula. Fissures were not detectable at the cathode face as long as the sample was kept in the sample holder. The cathode face of the sample appeared to be somewhat lighter in color than the anode face. At the anode face the sample appeared about as it had before treatment.

Only when the sample was removed from the sample holder did the complete change in physical appearance become apparent. In all samples, except the 20/80, there were three distinct zones. At the cathode end there was the brittle material for a distance of about .1 in. Going toward the anode there was next a very thin zone, about .025 in. thick, which was very hard and quite difficult to break up and re-mix with the rest of the sample. When wet this zone appeared darker than the remainder of the soil. The rest of the sample

TABLE 1

COMPILATION OF TEST DATA

Sample Illite/Sand	Atterbergs Limits						Moisture Content				$k_h \times 10^{-6}$ cm/sec		$k_e \times 10^{-6}$ cm^2/volt sec		Void Ratio
	Before			After			Initial	Final							
	L L	P L	Ip	L L	P L	Ip		Cathode	Anode	Middle	Before	After	form.	tang.	initial
90/10	41.3	25.4	15.9	50.4	26.9	23.5	.398	.372	.398	.389	.439	—	13.7	35.5	1.13
80/20	41.7	20.3	21.4	46.5	25	21.5	.34	.334	.370	.339	.366	.0447	7.17	12.3	1.008
70/30	34.9	20.0	14.9	36.8	20.7	16.1	.319	.395	.340	.321	.1325	.086	6.64	42.8	1.002
60/40a	29.7	17.2	12.5	36.9	17.2	18.8	.293	.292	.303	.297	1.335	.0952	5.5	25.7	.886
60/40b	31.1	17.3	13.8	33.7	17.9	15.8	.281	.269	.307	.292	.1987	.0809	5.94	26.3	.812
50/50	29.4	15.6	13.8	31.8	16.5	15.3	.261	.258	.265	.267	.187	.0918	4.78	22.45	.842
40/60	23.8	13.5	10.3	26.6	15.7	10.9	.228	.212	.224	.218	.260	.1184	4.98	12.85	.662
30/70	21.3	14.5	6.8	22.9	15.8	7.1	.192	.209	.210	.194	.2255	.0877	4.32	8.15	.533
20/80	17.8	—	—	18.6	—	—	.184	.190	.187	.1725	100.3	428	0	0	.587

appeared as it did when initially placed in the holder. This definite formation of a laminated structure is in agreement with Casagrande's finding (7) that clay samples tended to revert to a more natural arrangement during electro-osmosis. Tarran (18) and Butler (3) observed the same arrangement.

Immediately upon its removal from the sample holder, the cathodic zone fissured badly. A section of each treated sample was set aside to dry. After drying it was noted that the cracked, cathodic section had a tendency to curl upward away from the remainder of the soil with the hard, thin layer and the thick, anodic layer remaining intact. The thin layer dried out to the lightest color, the cathodic zone next darker, and the anodic zone darkest of all. When a thoroughly dried section was placed in water, it adsorbed the water and slacked so rapidly that it almost seemed to disintegrate. There was no evidence of any permanent hardening due to the nickel-silver electrodes.

There was no method available to the author to determine the constituents of the three separate zones. Consequently, it is impossible to know just what caused the formation of the zones. However, it does seem logical to assume that the rearrangement could be the result of electro-phoresis plus some deposition of electrode material. The cathodic zone did appear to be more granular than the other zones.

Moisture Content

The values of moisture content for the sample as a whole prior to treatment and for various zones within the sample after treatment are shown in Table 1. The reason for making the final determinations at the cathode, middle, and anode of the sample is that there were variations of structure across the sample as previously mentioned. It was indicated in PROCEDURE that the sample had water added to place it approximately at its liquid limit so that a normal, natural clay condition would be realized. Table 1 shows that initial moisture contents were slightly under the liquid limit except for the 80/20 sample which is believed to have an incorrect liquid limit value. Casagrande has indicated (6) that samples should be near the liquid limit when being tested for electro-osmotic characteristics.

In almost every case it can be noted that after treatment the moisture content is lower at the cathode, higher at the anode, and some intermediate value in the middle which may be higher or lower than the initial value. This variation of moisture content in the middle zone is probably due to variations in the distance from the anode and cathode of the various samples taken. These changes in moisture content are in agreement with the results of Tarran (18) and Butler (3) who worked with 100% illite. Since there is a definite rearrangement of soil structure, it seems likely that this change causes changes in the void ratio of the zones formed. The

change in voids would then provide an explanation for the change in moisture content with the zone of greater voids having a higher moisture content. The increase of moisture for the 20/80 sample at both the anode and cathode is probably due to a loss of fine material at both faces during testing. It was observed that disturbances of the water caused fine material to leave the sample and enter the water.

The other important factor to notice is the generally small changes of the moisture content. Although there is a decrease at the cathode, a close check will show that, considering the cross section as a whole, there is little if any decrease in overall moisture content. This result is contrary to most tests which report a substantial reduction of moisture. However, it is noted that most of the other investigators have used higher electrical gradients. The author's results agree more closely with field applications where the gradient is also low.

<u>Atterberg Limits</u>

The values of Atterberg limits before and after treatment are shown in Table 1.

Due to time limitations the values for liquid limit are based on only one determination for each sample. If more values could have been obtained it is believed that more uniform results would be produced. It seems that either the 80/20 or the 90/10 value must be in error. Regardless of these inaccuracies, it is the changes which took place as a

result of treatment that is important. In every case the liquid limit after treatment was higher than before. With the exception of the 60/40 (a) sample the plastic limits were all increased after treatment. The plasticity index was also increased for every sample. There is no set pattern for the amount of increase of each of the limits. The 90/10, 80/20, and 60/40 (a) samples present the most erratic variations, while the remainder have rather uniform, relatively small changes. Since only one of each sample was tested, it is impossible to know what effect the time of treatment has on the limits.

Other investigators have obtained results agreeing with these, while others have found just the opposite. Since Tarran (18) and Butler (3) obtained similar results for 100% illite it appears that the increase of limits after treatment is characteristic of this particular illite with the electrodes used.

Hydraulic Permeability

Values for the hyrdaulic coefficient of permeability, k_h, before and after treatment are shown in Table 1.

The author has no definite explanation for the erratic values obtained before treatment. It could be caused by undetected voids in the sample or by an uneven distribution of coarse material so that relatively porous zones existed in certain samples. One would assume that values would either increase with decreasing illite content or that they

would remain almost constant until the sand content became great enough to overcome the effect of illite activity. However, the values as determined are all quite low prior to treatment except for the 20/80 sample at which point the sand content became so large that the material was relatively permeable. After treatment most of the samples had about the same permeability, and in all cases the samples were more impervious after treatment, except the 20/80. Since the samples did exhibit this decreased permeability it is believed that it was due to the rearrangement of the soil. One of the zones formed by treatment probable was more impervious than the others resulting in a lower permeability for the sample as a whole.

One other possibility exists which would tend to decrease the permeability after treatment. It was noticed that many small bubbles adherred to the cathode when the current was turned off. These bubbles remained during the final permeability test. It could be that gas bubbles also remained in the sample thereby reducing the area through which flow would normally occur. Since k_h is inversely proportional to the cross sectional area of the sample, if a reduced area was the effective area, the value of k_h would then be greater than as shown. A sample computation is shown in Appendix B.

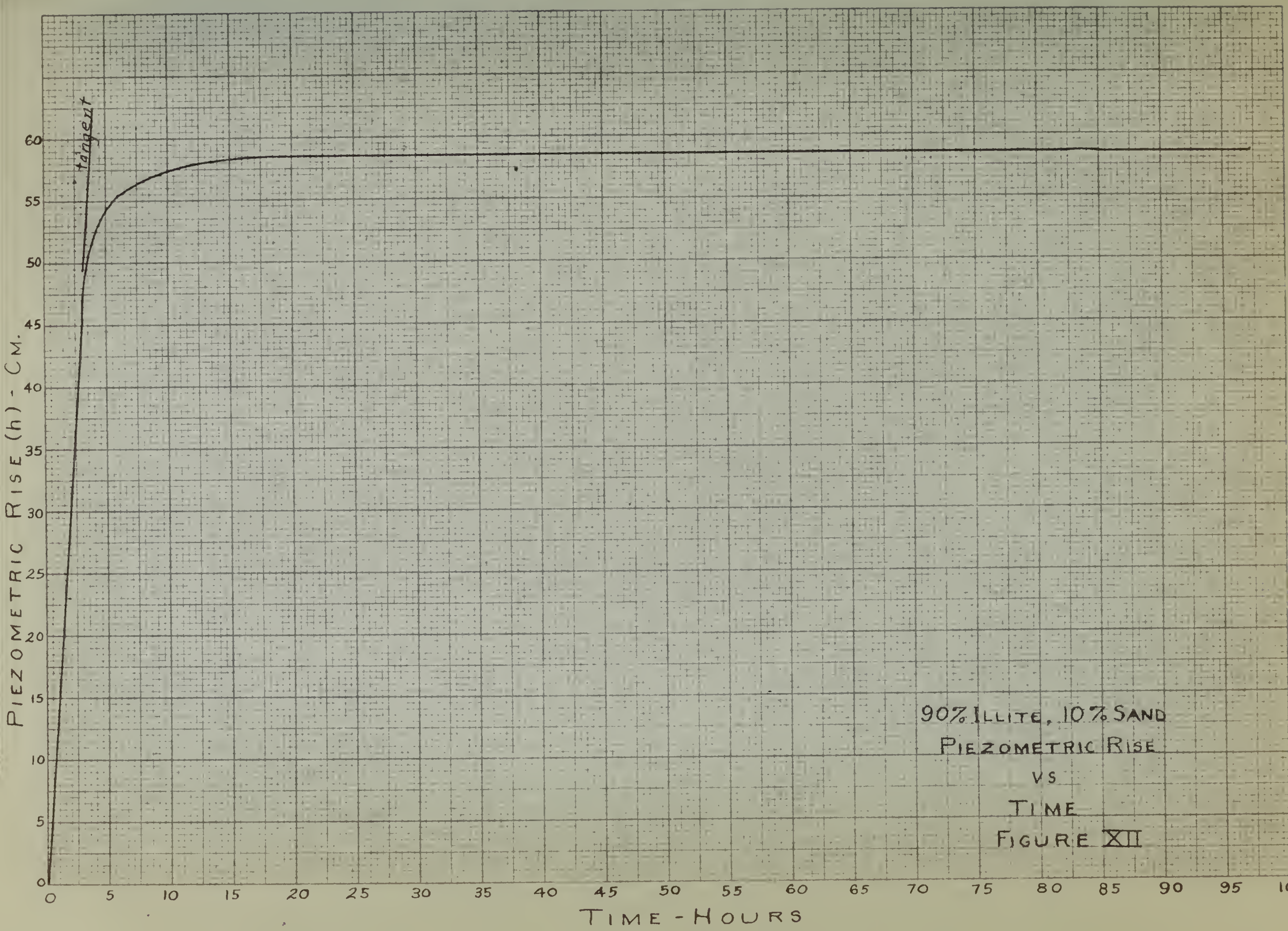
Karpoff noted (11) that a majority of the investigations which he had studied showed the sample to be more pervious after treatment. However, one of the samples which

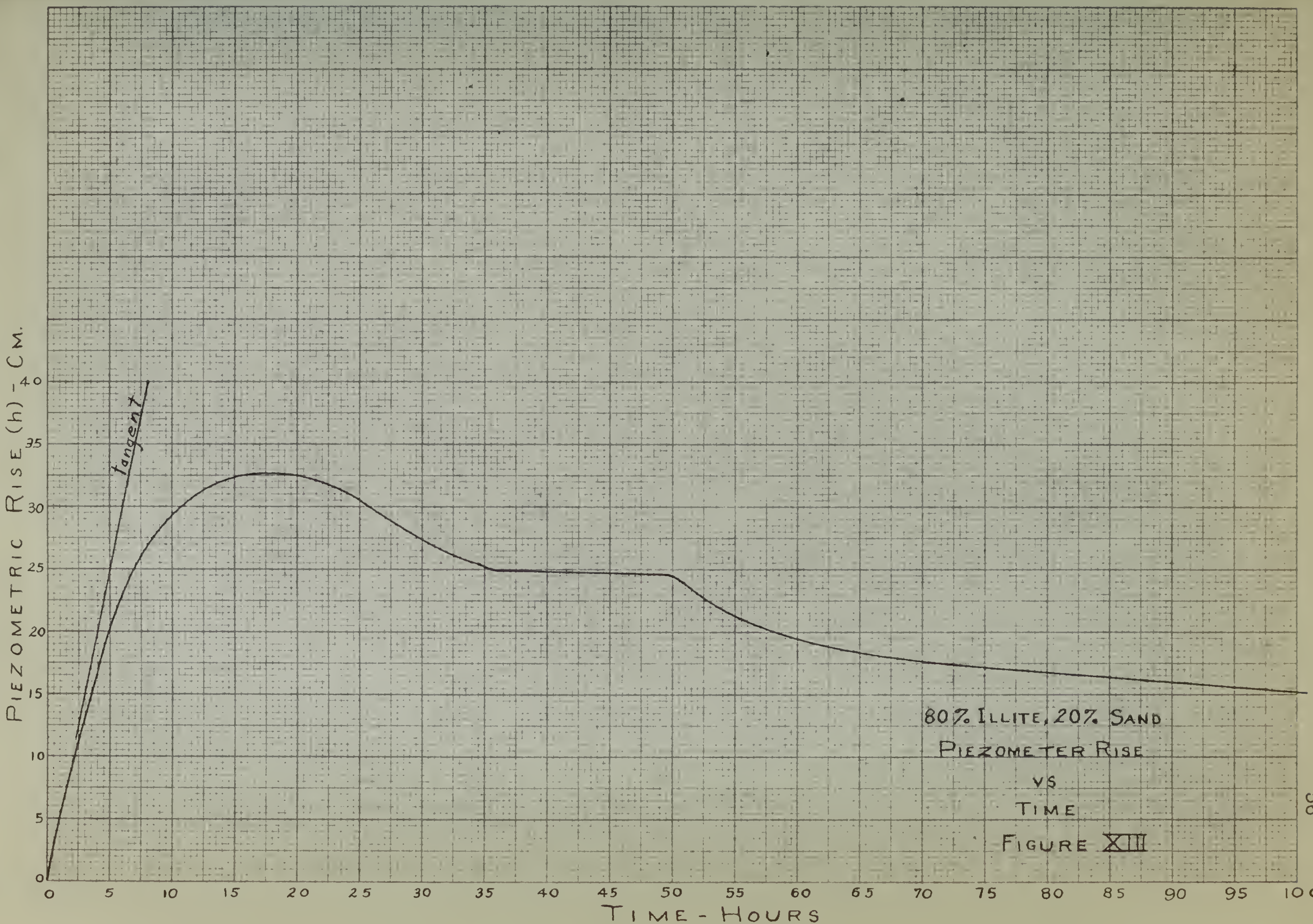
he tested contained some illite and showed a decrease in permeability after treatment. Both the soil being tested and the electrode material probably have an effect on this characteristic.

Height of Piezometric Rise and Electro-osmotic Permeability

Since the purpose of determining the height of piezometric rise is to provide a means of determining the electro-osmotic coefficient of permeability, k_e, the two factors are discussed together. The values of k_e as determined by the formula method and by the tangent method as outlined in THEORY are shown in Table 1. The height of rise vs time curves with corresponding tangent lines are shown in Figures XII - XIX inclusive. Sample computations for obtaining k_e are in Appendix B; the point of maximum rise was used for computing k_e by the formula.

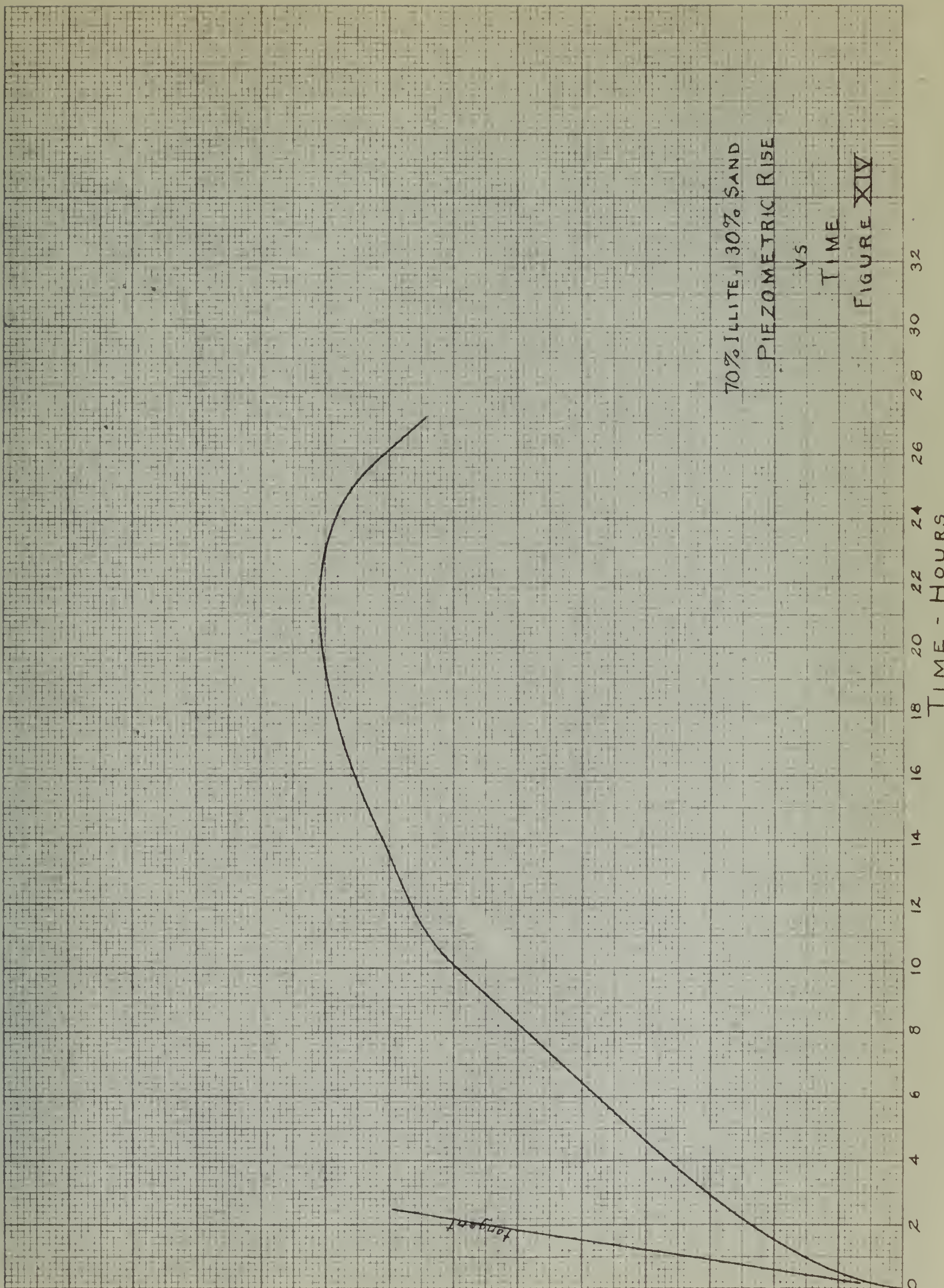
In order to determine an accurate value of k_e by either method, the height of piezometric rise must be correct. However, as indicated in PROCEDURE, obtaining correct values of height of rise is impossible due to the continual discharge of gas at the cathode. Gas bubbles which formed were very tenacious. By tilting the base of the electrosmometer and by agitating the water in the cathode side by squeezing the flexible tube at the bottom of the cylinder it was possible to remove the majority of the gas bubbles in some instances. The readings which were taken immediately thereafter are so indicated on the raw data sheets, Appendix A.

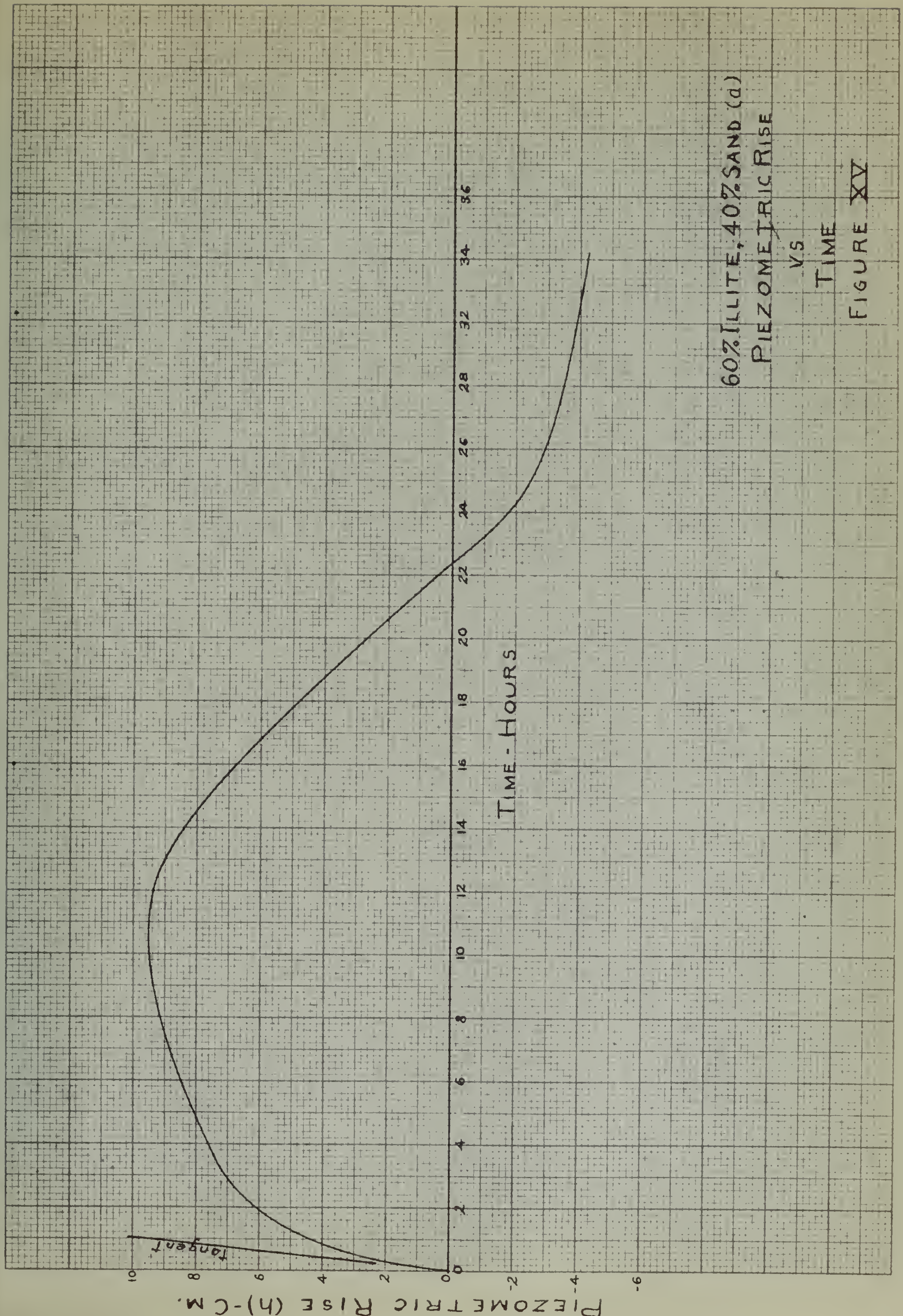

tangent
60
55
50
45
40
35
30
25
20
15
10
5
0
Piezometric Rise (h) - Cm.
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
Time - Hours
90% Illite, 10% Sand
Piezometric Rise
vs
Time
Figure XII

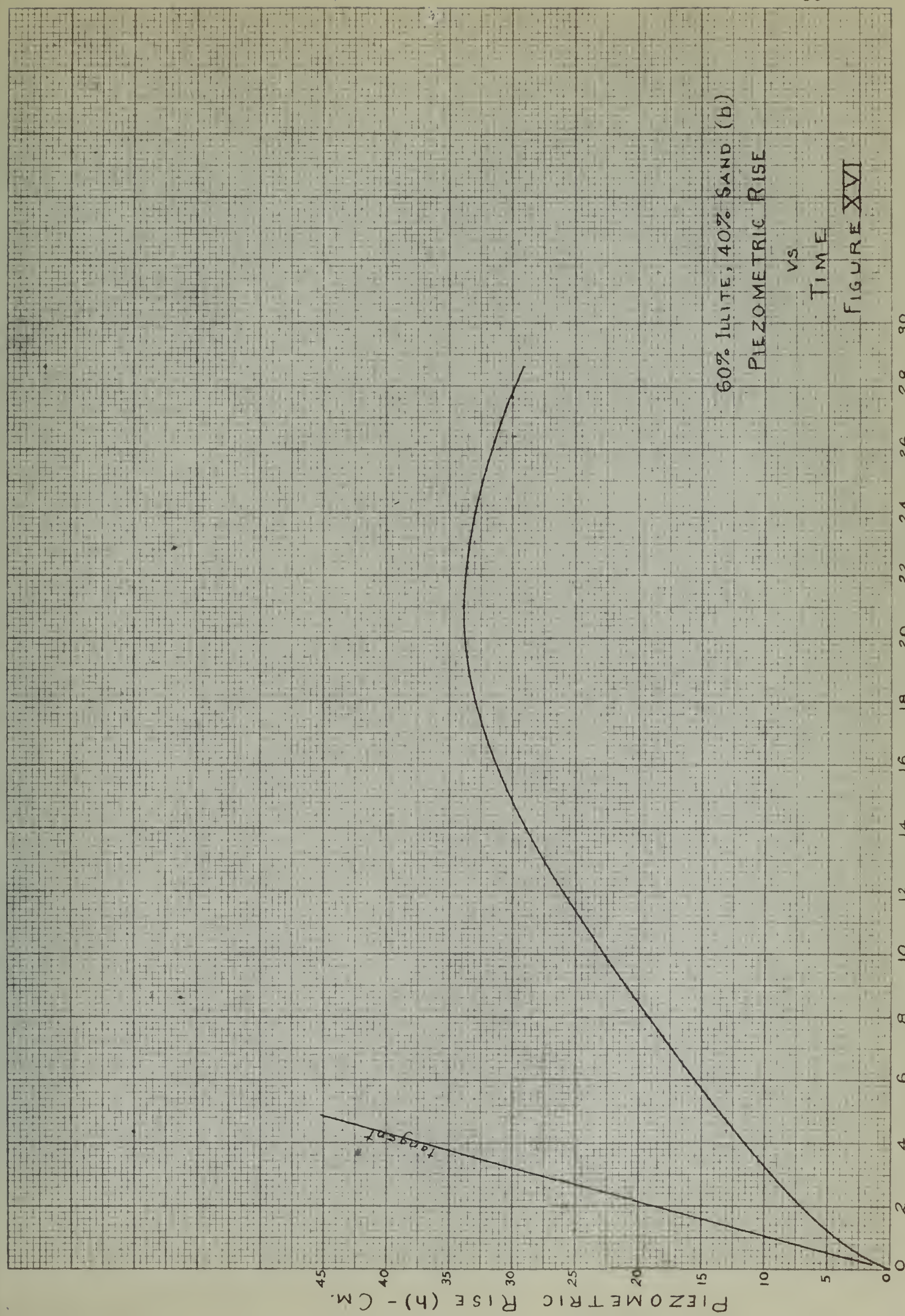


80% Illite, 20% Sand
Piezometer Rise
vs
Time

Figure XIII


70% Illite, 30% Sand
Piezometric Rise
vs
Time
Figure XIV
Time - Hours
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
Piezometric Rise (h) - Cm.
0
5
10
15
20
25
30
35
40
45
50
tangent


60% ILLITE, 40% SAND (d)
PIEZOMETRIC RISE
VS
TIME
FIGURE XV
TIME - HOURS
PIEZOMETRIC RISE (h) - CM.
tangent
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
32
34
36
10
8
6
4
2
0
-2
-4
-6


60% Illite, 40% Sand (b)
Piezometric Rise
vs
Time
Figure XVI
tangent
Time - Hours
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Piezometric Rise (h) - Cm.
0
5
10
15
20
25
30
35
40
45

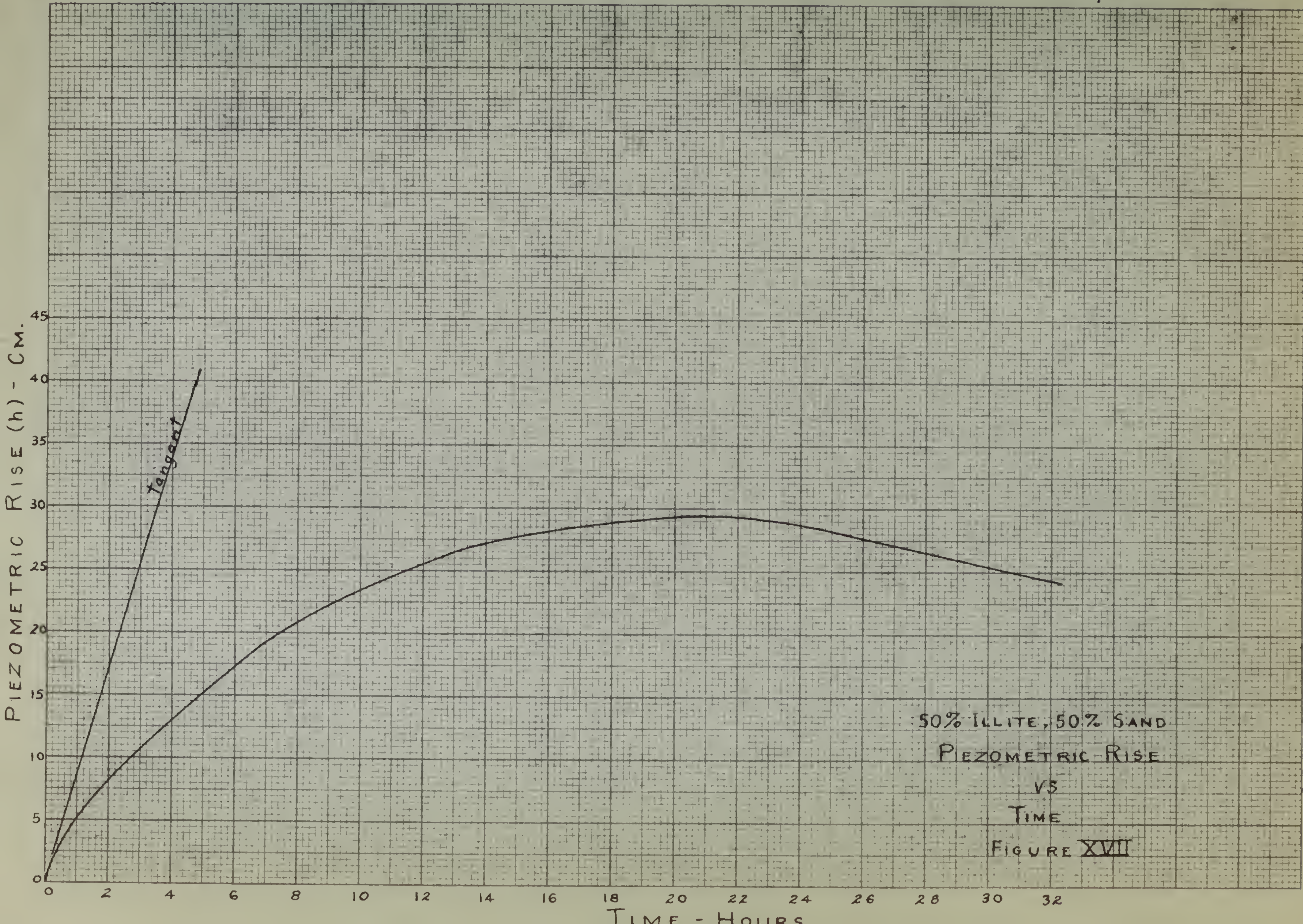
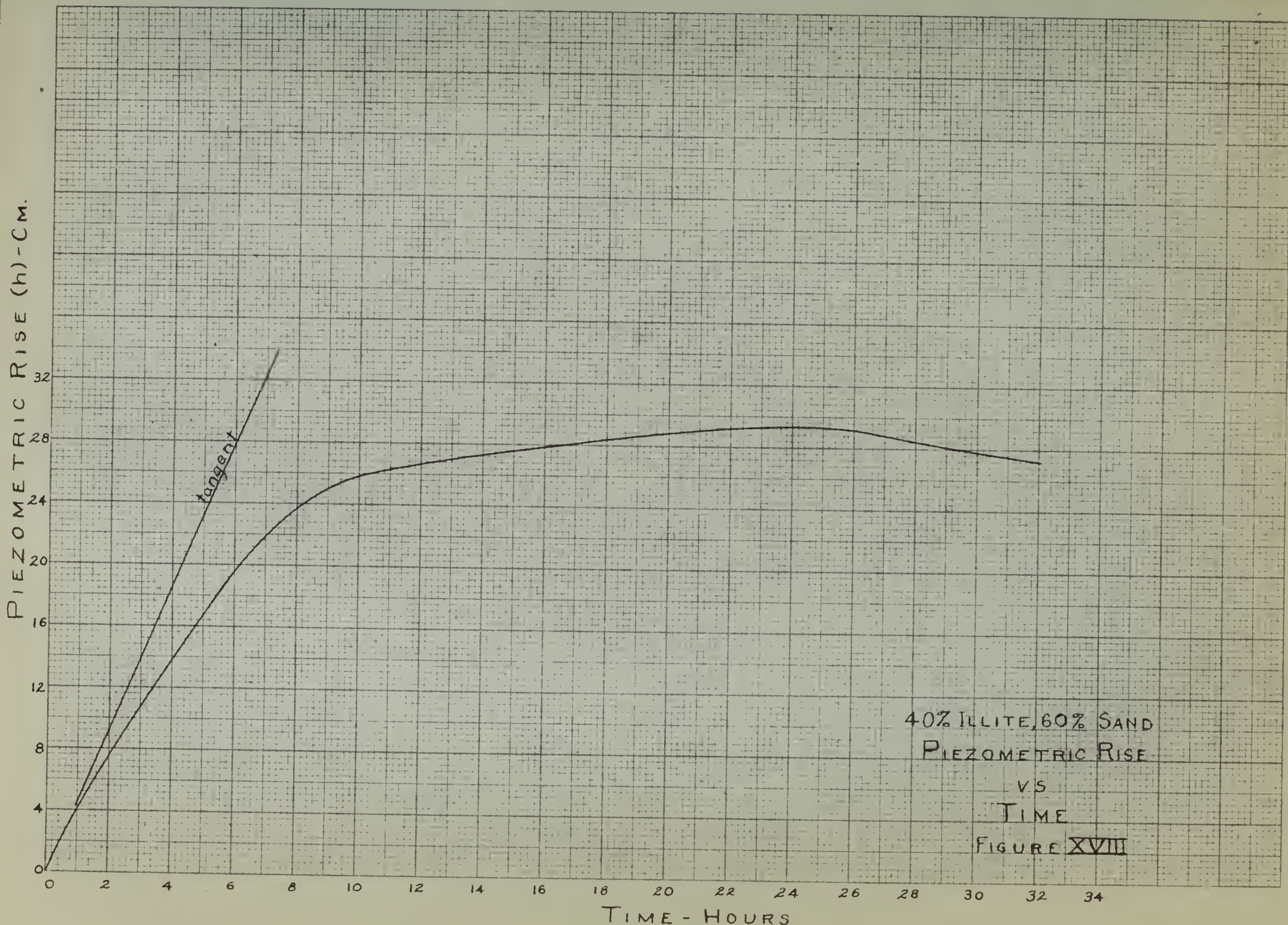
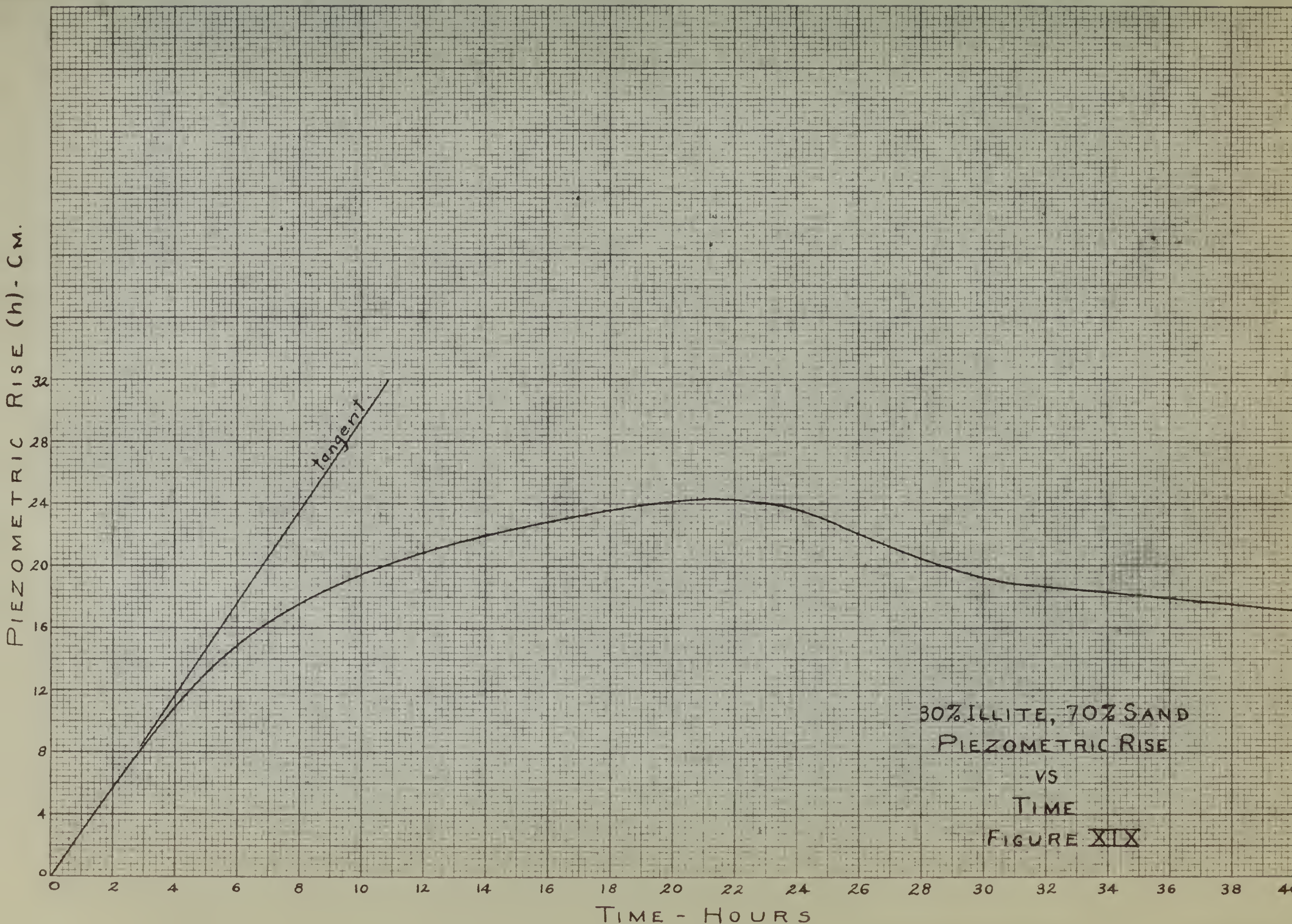

50% Illite, 50% Sand
Piezometric Rise
vs
Time
Piezometric Rise (h) - Cm.
Time - Hours
Tangent
0
5
10
15
20
25
30
35
40
45
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

Figure XVII



40% Illite, 60% Sand
Piezometric Rise
vs
Time
Figure XVIII



30% Illite, 70% Sand
Piezometric Rise
vs
Time
Figure XIX
tangent
Piezometric Rise (h) - Cm.
Time - Hours
0
4
8
12
16
20
24
28
32
2
6
10
14
18
22
26
30
34
36
38
40

Added to this inaccuracy was the inability of the author to obtain continuous readings from the beginning of a test until the maximum rise was reached. Time out for classes and for sleep made this impossible. Consequently the figures showing the rise vs time curves are at best the author's own interpretation of how these two factors are related. The maximum rise generally decreased with decreasing illite content and the maximum occurred from 17.5 to 24 hours after the start, except for the 60/40 (a) sample.

The values obtained for k_e by both methods do appear satisfactory when compared with the values of k_h. The values of k_e generally decrease with decreasing illite content which was expected. The values obtained by formula range from 20 to 30 times the values for k_h, while the tangent method yields values 40 to 320 times as great. The value of k_h for the 60/40 (a) sample before treatment is obviously in error and is not included in the above comparisons. This shows the definite possibility of removing the water faster by electrical means than by natural drainage.

Butler (3) was able to obtain close agreement between formula and tangent values of k_e because his curves had an early, straight line portion which very nearly coincided with the tangent line. This was no where the case in the author's tests.

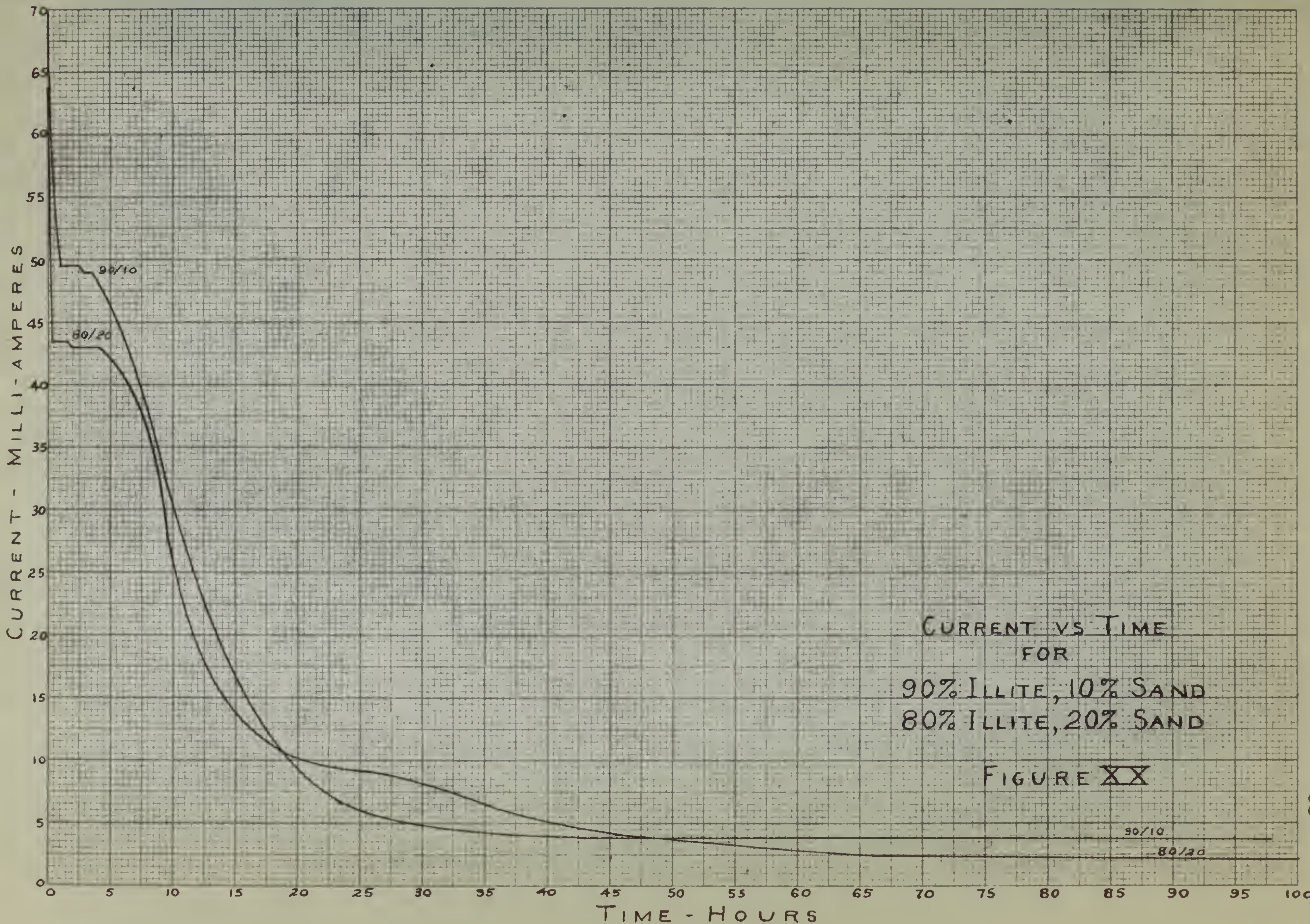
Applied Voltage

It was originally intended to maintain a voltage

gradient of 1.5 volts/cm. However, when it became obvious that the samples would be at different thicknesses at the start of the various tests, it was decided to hold the voltage constant and let the gradient vary. Initial gradients vary from 1.36 - 1.56 volts/cm. The values of k_e obtained are somewhat different than would have been the case for a constant gradient. However, the general nature of the results as outlined above would not have changed. Also, it would have been impossible to accurately set the voltage for a constant gradient since the scale on the voltmeter was not large enough to obtain exact fractional values. It was possible to set the voltage at 2.7 volts for each reading which was made. The re-setting of voltage was necessary because of variations in the voltage supplied to the laboratory.

Current Changes

The change of current with time is shown in Figures XX - XXIII inclusive. The current was a maximum at the start of each test, and it immediately started to decrease. It decreased very rapidly during the first hour. A steady flow condition then existed for a varying length of time for each sample until the illite content was reduced to 30%. This small period of relatively uniform flow has not been generally noted in other tests. Christensen (8) has a current vs time curve with a steady flow for about 20 hours. His sample was much larger than the author's. Casagrande (4) indicates that in application the current decreases only when



Current vs Time
for
90% Illite, 10% Sand
80% Illite, 20% Sand

Figure XX

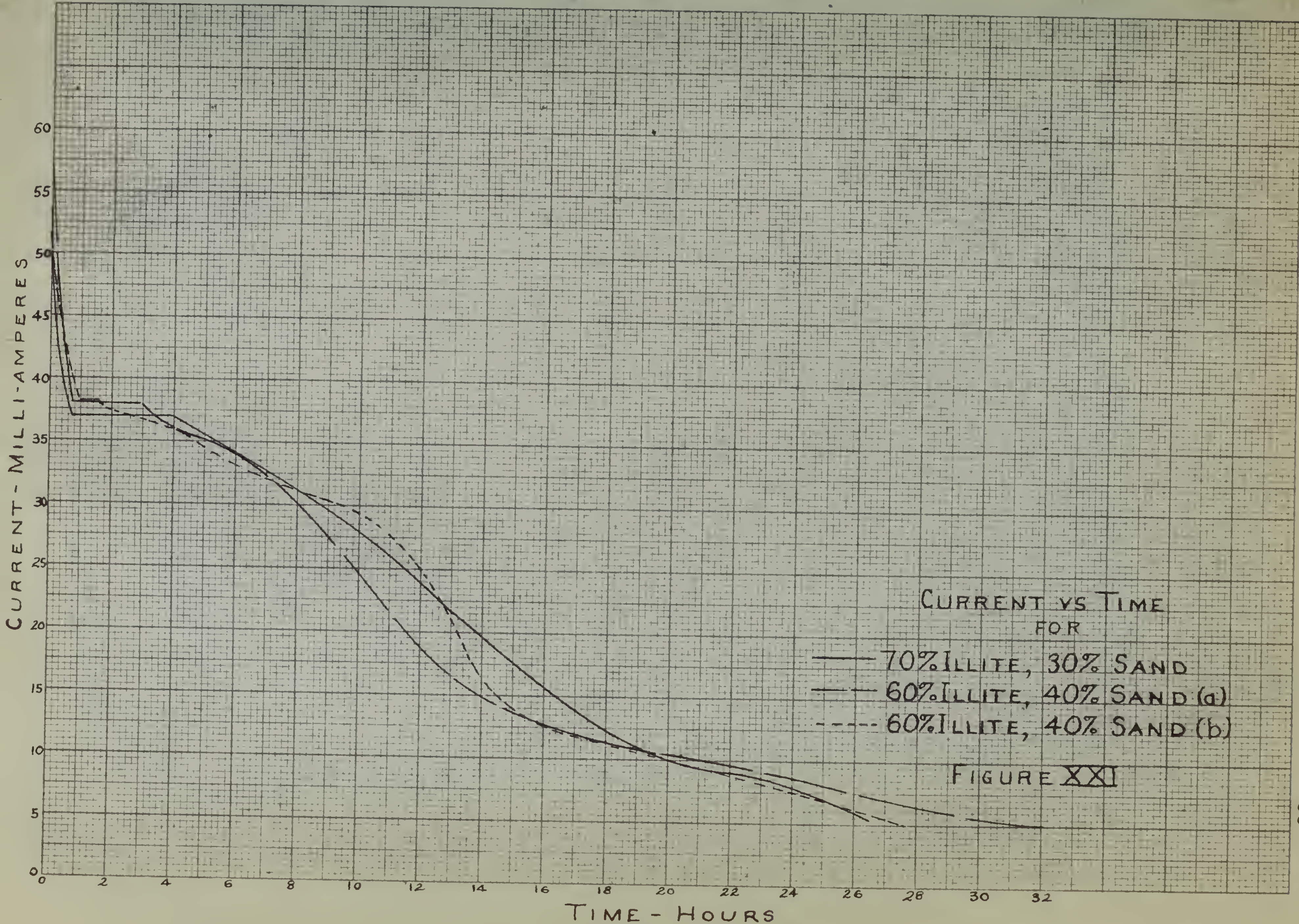
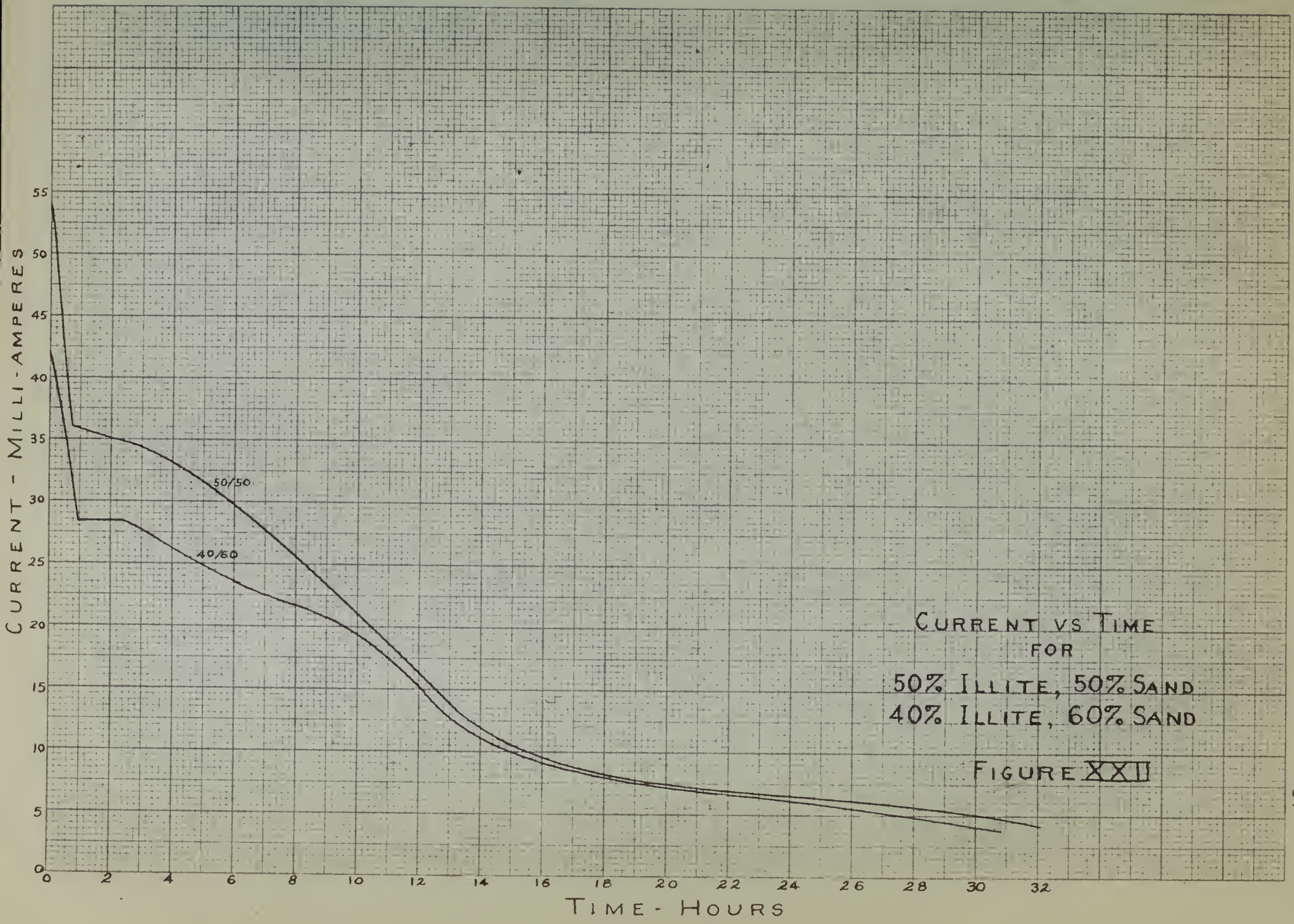

CURRENT VS TIME
FOR
70% ILLITE, 30% SAND
60% ILLITE, 40% SAND (a)
60% ILLITE, 40% SAND (b)
CURRENT - MILLI-AMPERES
TIME - HOURS
0
5
10
15
20
25
30
35
40
45
50
55
60
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32

FIGURE XXI


CURRENT VS TIME
FOR
50% ILLITE, 50% SAND
40% ILLITE, 60% SAND
50/50
40/60
CURRENT - MILLI-AMPERES
TIME - HOURS
0
5
10
15
20
25
30
35
40
45
50
55
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
FIGURE XXII

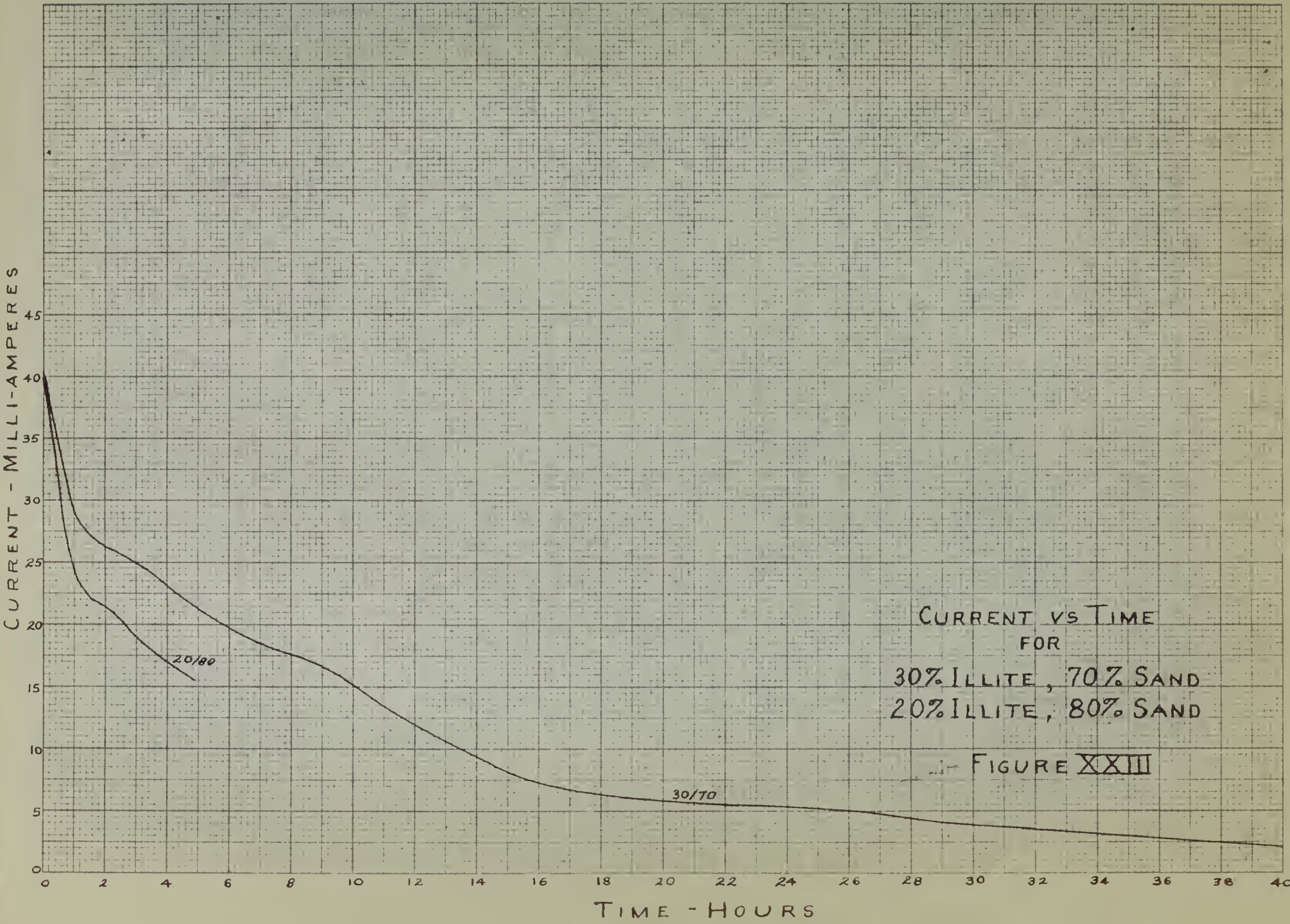


FIGURE XXIII

the moisture content has been greatly reduced which was certainly not the case here. Tarran (18) and Butler (3) do not indicate a period of steady current flow. Actually, there does not seem to be a standard answer to just why the current decreases as it does. It is probable that the ionization of the electrodes and base exchange within the sample cause a rapid increase of sample resistance. It may be that the steady flow values are approximately equal to values which would be obtained in field applications for the same gradient.

In general the maximum values of current decrease with decreasing illite content. Casagrande (4) notes that the magnitude of current is dependent largely on grain size.

Although only the 90/10 and 80/20 samples were tested long enough to have the current approach a relatively constant, low value, it is believed that this condition would be reached for all samples after a certain time. Time did not permit the tests to continue for lengthly periods. Also it was believed that no useful purpose would be served by continuing the test past the point of maximum piezometric rise.

Changes in Electrodes

The change in weight of the electrodes for each test is shown in Table 2. The total loss in weight for the anode was 6.313 gm. The cathode gained a total of .252 gm. It was necessary to resolder each electrode to its connecting wire once during the tests. The copper wires were exposed for a

TABLE 2

ELECTRODE WEIGHTS

SAMPLE Illite/ Sand	CATHODE WEIGHT'		ANODE WEIGHT'	
	Before	After	Before	After
90/10	143.710	143.750	57.260	56.110
80/20	143.750	143.782	56.110	55.040
70/30	143.782	143.795	55.040	54.288
60/40 (a)	143.795	143.820	*55.685	54.936
60/40 (b)	**145.165	145.209	53.792	53.096
50/50	143.820	143.861	54.936	54.329
40/60	143.861	143.881	54.329	53.792
30/70	145.209	145.235	53.096	52.588
20/80	145.235	145.256	52.588	52.344

' all weights in grams

* wire resoldered to anode before this test

** 60/40 (b) sample not tested in chronological order shown and wire was resoldered to the cathode before this test

short length at the point of connection and evidently were ionized sufficiently to cause breakage of about half of the individual wires. Therefore, some of the weight changes can be attributed to the wire. However, it is obvious that the anode was the principal source of weight variation.

The anode thickness was also checked and it was discovered that the reduction in thickness was not uniform over its area. Near the wire connection the reduction amounted to .007 in. Between the edge of the anode and the circle of contact of the cap on the plunger the reduction amounted to .005 in. The reduction over the area in contact with the cap on the plunger amounted to .004 in. This variation seems to indicate a non uniform distribution of current flowing from the anode.

Since it was not possible to conduct a chemical analysis of the samples or of the water in the cylinder, the place of deposition of the anode material is unknown. It is not known whether the increase in cathode weight is due to material from the anode or to the introduction of very fine material from the sample.

pH Values

After every test the water in the cylinder had a similar appearance. The water in the cathode side remained clear and had no precipitate in it. The water in the anode side took on a faint green color, and a cream colored, fluffy precipitate settled out in the bottom of the cylinder. The pH of the water in the cathode side varied from 10.65 - 10.8

while that in the anode side varied from about 5.7 - 6.1. Facilities were not available for analyzing the water. These results are in agreement with those obtained by Tarran (18) and Butler (3).

Variations in Sample Thickness and Void Ratio

The ability of electro-osmotic action to produce consolidation of the sample was not clearly demonstrated by this series of tests. Although the author has not tabulated the void ratio or change in thickness for each reading, a quick check of the raw data, Appendix A, will indicate why this was not done. In some cases there was a net decrease in thickness and in others there was a net increase. Also, the manner in which the thickness varied during each test was not uniform. A majority of the samples did consolidate slightly and then expand. The maximum void ratio change was no more than about 3%. In most cases the void ratio could be considered as relatively constant.

It was hoped that some relationship could be obtained between void ratio and the values of k_h before and after treatment as well as between void ratio and the values of k_e obtained by the two methods. Casagrande (6) indicates that a straight line relationship exists between the ratio of $\frac{e}{1+e}$ and k_e. Vey (20) found a straight line relationship between e and log k_e. However, it seems that neither of these relationships is particularly meaningful. This is true because e could remain constant and the straight line relationship would still hold. It would be of possible value if the

change in void ratio could be directly related to the change in k_h which results from treatment. Consequently, the author is inclined to believe that ionization of the anode together with particle rearrangement resulting from electrophoresis causes the changes in k_h. There are no results from these tests which actually give an indication of the reasons for changes in k_e with time. Base exchange, change of electrolyte concentration, and change of zeta potential are all obvious possibilities.

Values of initial void ratio tabulated in Table 1 show a generally decreasing value as the illite content decreases. This was to be expected. The author has indicated the void ratio at the start of each test on the raw data sheets. This will permit any interested reader to quickly find the void ratio for any particular reading if he so desires.

It should be noted that there is generally a definite decrease in void ratio at the start of a test as compared to that listed as the initial value. It was hoped that the values would be almost equal for a given sample, since each sample was inserted the same distance into the sample holder. It is believed that the sample may have been pulled slightly outward and perhaps tilted during the process of cutting the sample off. This, together with rebound, would make the sample thinner at the start of the test than at the time it was placed in the holder. The accuracy of either value is somewhat doubtful to say the least.

Induced Voltage in Samples

After the power supply was turned off a small current was found to be flowing in a direction opposite to the normal supply current. This was true for each sample tested. The current varied from 1.3 - 4.5 ma, and the voltage across the sample varied from .2-.7 volt. The higher values of both occurred in the samples having the highest illite content. The amount of current and voltage both decreased as soon as the circuit was closed to allow continuous flow. After one test this current was allowed to flow for about 24 hours after which time the current and voltage were about half of the initial values.

Production of a streaming potential is a well known phenomena of electro-osmosis. Since the streaming potential opposes the applied potential, it appears that this residual potential could be a result of the streaming potential. The author had believed that the streaming potential existed only while the water was passing through the soil. If this is so, the residual potential may be one which is built up solely by the soil in resistance to the applied potential.

Since this potential opposes the applied potential, it acts as an increased resistance and could account for some of the decrease in current previously discussed. However, the low values of current flowing from the sample would indicate that it would not be the predominant factor in causing a reduction in flow of current.

B. 90% Illite, 10% Sand Test

One look at Figure XII is enough to indicate that something was different from the other tests. The height of rise quickly reached a maximum and remained there throughout the test. The basic cause of this was the formation of gas bubbles in the cathode side of the cylinder. This was the first test run by the author, and it was rather startling to say the least. The bubbles formed finally into one large bubble which started at the right end plate and progressed toward the opening leading to the piezometer tube. It was felt that a large part of the bubble would pass upward through the piezometer tube as soon as the opening was reached. However, this did not occur, and the bubble continued to grow in size. After the height of rise had reached its constant value of 58 cm the size of the bubble also remained constant. However, small bubbles of gas did continue to pass upward through the piezometer tube. When the author realized that this condition could continue indefinitely a steel rod attached to a string was dropped down the piezometer tube. This disturbance was sufficient to cause the water in the piezometer tube to drop to an elevation of about 17 cm. During the test a yellow colored flocculent substance developed in both chambers of the cylinder. Also a strong film developed on top of the water (at the bottom of the gas bubble) in the cathode side. The author cannot explain why at least part of the bubble did not pass off to the atmosphere. The flocculent structure is believed to be the result of foreign

matter in the water, on the inner faces of the electroosmomotor or, on the electrodes. This should be adequate warning to future users of the equipment to make certain that it is properly cleaned prior to being used.

Prior to each of the remaining tests all parts of the electrosmometer were cleaned and rinsed in distilled water. The container for the distilled water was emptied, cleaned and refilled with fresh distilled water. No more problems of this type were encountered.

C. 60% Illite, 40% (a) Sand Test

Examination of Figure XV shows that the maximum rise obtained for the 60/40 (a) sample was much lower than it should have been. Also, the decrease in rise after the maximum continued until negative values were obtained. This was not expected, but at the time the author thought it could be a natural occurrence brought about by the increase in sand content. Testing was continued with the 50/50 sample and then the 40/60 sample. When both of these yielded normal results another 60/40 sample was tested, and it too was found to fit the normal pattern.

The result of the 60/40 (a) test indicated a definite reversal of electro-osmotic flow. The cause of this reversal was finally determined to be due to the resoldering of the lead in wire to the anode before the test started. Some liquid flux was used. Although the anode was rinsed after the soldering was completed and then oven dried, it is

believed that some of the flux remained in the metal. Consequently, when electro-osmosis started again the flux left the anode and went into the sample. There it changed the concentration sufficiently to cause a reversal of the double layer with a resulting change of direction of flow. There was no other changed condition which could have caused the reversal.

D. 20% Illite, 80% Sand Test

This test is discussed separately, because the hydraulic permeability became so great that electro-osmosis did not take place. There was still a large increase of k_e over k_h for the 30/70 sample. The ratio of illite to sand that exists at the exact stopping point of electro-osmosis is unknown. The loss of the effect of illite on the sample was marked in this test. The plastic limit could not be determined. There was so little binding of soil particles that the agitation of the water in the cathode side caused fine material to be washed out into the anode section. This disturbance of the soil probably resulted in the increased value of k_h after the test was over. During the test the level of water in the piezometer tube would fall when gas bubbles were released. However, the heads in the anode and cathode sides would quickly become equal due to the high hydraulic permeability.

A 90/10 sample had been prepared for the next test. However, since its permeability was so great that the top

surface could not be kept covered with water for 24 hours, it was not tested. It was possible to keep water on the top of the 20/80 sample during preloading.

One other bit of useful information was obtained from this test. The permeability of the electrode material was not definitely known, and therefore, its effect on the permeability values obtained was unknown. However, after obtaining the high values of permeability for this sample, it was known that the electrodes would have no effect on the low values obtained for the other tests.

PART VII

CONCLUSIONS

When studying the conclusions it is most important that the conditions under which the results were obtained prior to reaching the conclusions be constantly kept in mind. The conclusions presented in this section are based solely on the results obtained by the author's experiments. Some factors which are almost universally accepted as being a result of electro-osmotic treatment cannot be verified here. The fact that they are not recorded here does not necessarily mean that the author does not agree that they generally result. However, the fact that they did not result only brings more clearly to focus the necessity of fully presenting the conditions under which the tests were made and keeping these conditions in mind at all times. Pertinent factors which should be kept in mind for this study are: 1) the low voltage and voltage gradient employed; 2) the very small size of sample which was used; 3) the relatively low, total moisture content of the samples; and 4) the varying content of illite.

The following are the author's conclusions:

1. The electrosmometer as used does not provide information which will permit an accurate determination of electro-osmotic coefficient of permeability. However, it will permit the user to determine relative values of hydraulic and electro-osmotic coefficients of permeability, and from this viewpoint it is an adequate piece of equipment.

2. Electro-osmotic treatment of preloaded, small samples of illite and sand while under a constant load of 1/4 T/ft^2 does not cause an appreciable additional consolidation of the soil.

3. Electro-osmotic treatment of an illite and sand combination using nickel-silver electrodes results in an increase in liquid limit, in plastic limit, and in plasticity index over the values obtained for an untreated sample.

4. Electro-osmotic treatment of an illite and sand combination produces three zones of varying moisture content within the sample. The zone adjacent to the cathode has the lowest moisture content, the zone near the anode has the highest content, and the zone between the anode and cathode has an intermediate value. For the sample as a whole there is no marked change in moisture content from the value which existed before treatment.

5. Electro-osmotic treatment of an illite and sand combination using nickel-silver electrodes changes the physical appearance of the soil by producing three distinct layers perpendicular to the direction of flow. A brittle, flaky layer is produced adjacent to the cathode; a very thin, hard layer is produced on the anode side of the cathodic layer just described; and a thick layer resembling the initial sample remains between the anode and the very thin layer.

6. Electro-osmotic treatment of an illite and sand combination with nickel-silver electrodes makes the soil more impervious to hydraulic flow after treatment. The hydraulic permeability after treatment is of approximately the same order of magnitude regardless of illite content.

7. Application of an external electrical potential to a sample composed of illite and sand produces a condition of electro-osmotic permeability which ranges from 20-320 times as great as the hydraulic permeability. A natural deposit of similar material should be much easier to drain by electrical methods than by natural drainage.

8. The degree of electro-osmotic permeability produced by electrical treatment decreases with decreasing illite content.

9. The activity of the illite is such that its influence in permeability relationships is predominant until the ratio of illite to sand becomes about 1 : 3. This means that permeability values obtained by electrical means would be much

larger than the natural values until the above ratio is reached. Below this ratio the effect of the illite is not pronounced and electro-osmotic flow does not exist.

10. The use of nickel-silver electrodes for electro-osmotic treatment does not produce permanent hardening in a sample composed of illite and sand within the length of time of treatment of these tests. The anode decomposes and with the present testing facilities it is impossible to ascertain the effect which each metal has on the electro-osmotic process. Electrodes of a single element should be used if possible.

11. Application of an electrical potential to a combination of illite and sand between nickel-silver electrodes results in an induced EMF being created in the sample. The EMF and the current produced by it are in opposition to the supply voltage and current. The EMF and current are readily measured and persist for an undetermined length of time.

PART VIII

RECOMMENDATIONS

There are a myriad of recommendations which could be made to improve the results obtained from electro-osmotic testing. Among the more obvious of these would be that additional analyses, such as chemical of water, chemical of soil, X-ray, differential thermal, etc., be made so that the actual changes taking place could be determined. However, it would be impossible for one person to run electro-osmotic tests and also obtain this additional data within the time available for doing his thesis. There are a few general recommendations which the author would like to make.

The electrode material should be of a single element. Although it would probably still not be possible to determine the exact chemical action taking place, it would be easier to determine whether the material was passing into the soil sample or into the water.

Performing tests similar to the author's but with different voltages would provide useful data on the effect of voltage gradient on producing consolidation, on decreases in moisture content and on variations in electro-osmotic permeability.

It is also recommended that tests similar to the author's be performed with the two other primary clay minerals, montmorillonite and kaolinite, as the active material. This would provide an interesting and valuable comparison of results

obtained under similar conditions for the different materials.

There are no particular recommendations to be made concerning the electrosmometer. In spite of its shortcomings its use is recommended, since it is believed that the relative type of data obtained by using it is most useful.

APPENDIX A

RAW DATA FOR EACH TEST

TABLE 3

RAW DATA

Sample: 90% Illite, 10% Sand
Sample Thickness at 0 Hours: 1.778 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.756
Void Ratio at 0 Hours: 1.13

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
3/7/57	1330	0.0	70	0.0	.135
	1345	.25	58	1.14	.135
	1400	.50	51	5.97	.135
	1415	.75	50.5	12.57	.1345
	1430	1.0	49.5	20.2	.1345
	1500	1.5	49.5	35.8	.134
	1530	2.0	49.5	47.5	.1337
	1600	2.5	49.5	47.5	.1337
	1630	3.0	49.0	46.8	.1335
	1700	3.5	49.0	52.6	.133
	1730	4.0	48.0	52.6	.133
	1900	5.5	45.2	54.5	.1324
	2000	6.5	43.5	54.6	.1318
	2250	9.3	33.0	58.5	.1314
3/8/57	0840	19.2	10.0	58.4	.130
	0950	20.3	9.0	58.7	.130
	1045	21.3	8.5	58.5	.1297
	1300	23.5	7.0	58.5	.1297
	1400	24.5	6.6	58.4	.1297
	1500	25.5	5.9	58.7	.1297
	1550	26.3	5.5	58.5	.1297
	2220	32.8	4.4	58.5	.1295
3/9/57	0915	43.8	3.8	58.5	.1288
	1935	54.1	3.6	58.4	.1283
3/10/57	1410	72.7	3.8	58.4	.128
	2145	80.3	3.9	58.7	.128
3/11/57	0845	91.3	3.7	58.4	.1316
	0950	92.3	3.7	58.4	.1318
	1155	94.4	3.7	58.7	.1352
	1315	95.8	3.7	58.7	.1345
	1540	98.2	3.6	58.4	.134

TABLE 4

RAW DATA

Sample: 80% Illite, 20% Sand
Sample Thickness at 0 Time: 1.732 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.752
Void Ratio at 0 Hours: .968

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
3/14/57	0800	0.0	64	0.0	.1538
	0815	.25	50	2.16	.1541
	0830	.50	43.5	6.48	.1541
	0845	.75	43.5	10.8	.1542
	0900	1.0	43.0	16.8	.154
	0930	1.5	43.5	17.1	.1541
	1000	2.0	43.0	23.6	.1539
	1100	3.0	43.0	39.2	.1541
	1200	4.0	43.0	17.9	.1549
	1425	6.4	40.0	22.8*	.1549
	1645	8.8	34.0	27.2*	.1549
	1745	9.8	27.0	38.5	.1549
	2240	14.7	14.0	32.4*	.154
3/15/57	0720	23.3	9.2	31.3*	.1507
	1330	29.5	8.3	27.2*	.1515
	2035	36.6	5.8	24.9*	.152
3/16/57	1035	50.6	3.6	24.8*	.1531
	1500	55.0	2.9	20.9*	.1534
	2110	61.2	2.5	19.3*	.151
3/17/57	1505	79.1	2.1	16.9*	.1513
3/18/57	0845	96.8	2.1	16.0*	.151
	1305	101.1	2.1	15.5*	.1515

* those readings which are most accurate due to release of gas just prior to reading

TABLE 5

RAW DATA

Sample: 70% Illite, 30% Sand
Sample Thickness at 0 Hours: 1.85 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.748
Void Ratio at 0 Hours: .866

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
3/21/57	1320	0.0	53.5	0.0	.1054
	1335	.25	44.5	2.16	.1060
	1350	.50	38.0	3.94	.1060
	1405	.75	37.0	10.40	.1060
	1420	1.0	37.0	8.00*	.1063
	1455	1.6	37.3	14.22	.1063
	1520	2.0	37.3	11.05*	.106
	1620	3.0	37.0	16.26*	.1066
	1720	4.0	37.0	17.15*	.106
	1935	6.2	34.0	23.90*	.1084
	2322	10.0	28.5	35.20*	.107
3/22/57	0835	19.3	10.7	44.60*	.1065
	1053	21.6	9.0	45.25*	.1072
	1142	22.4	9.0	42.20*	.1076
	1330	24.2	7.5	42.20*	.1081
	1440	25.4	6.65	41.65*	.1090
	1645	27.5	5.4	35.70*	.1095

* those readings which are most accurate due to release of gas just prior to reading

TABLE 6

RAW DATA

Sample: 60% Illite, 40% Sand (a)
Sample Thickness at 0 Hours: 1.924 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.744
Void Ratio at 0 Hours: .827

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
3/26/57	1145	0.0	57	0.0	.0777
	1200	.25	48.5	.89	.0778
	1215	.50	41.0	1.14	.0778
	1232	.80	38.0	3.68	.0771
	1245	1.0	38.0	5.46*	.0770
	1317	1.5	38.0	6.73	.0770
	1345	2.0	38.0	6.22*	.0762
	1445	3.0	37.5	7.36	.0770
	1600	4.3	35.5	9.28	.0770
	1606	4.4	35.5	5.96*	.0767
	1700	5.3	35.0	6.73*	.0769
	1730	5.8	34.5	8.00*	.0769
	2022	8.6	29.0	8.89*	.0770
	2226	10.7	23.0	9.40*	.0768
	2340	11.9	19.0	9.40*	.0767
3/27/57	1108	23.4	9.0	- 1.02*	.0764
	1155	24.2	8.6	- 2.03*	.0764
	1257	25.2	7.9	- 2.80	.0764
	1353	26.2	7.4	- 2.29	.0764
	1515	27.5	6.7	- 1.27	.0764
	1640	29.0	6.0	- 3.18*	.0766
	1954	32.2	5.0	- 4.32*	.0768

* those readings which are most accurate due to release of gas just prior to reading

TABLE 7

RAW DATA

Sample: 60% Illite, 40% Sand (b)
Sample Thickness at 0 Hours: 2.00 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.744
Void Ratio at 0 Hours: .825

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
4/6/57	0925	0.0	51.5	0.0	.0478
	0955	.5	43.0	1.14	.0489
	1025	1.0	38.0	2.03*	.0490
	1055	1.5	38.0	3.94	.0495
	1125	2.0	37.5	10.03	.0500
	1155	2.5	37.0	8.9 *	.0503
	1225	3.0	37.5	10.07	.0505
	1330	4.1	36.0	15.60	.0507
	1415	4.8	34.5	16.40	.0517
	1454	5.5	34.0	16.25*	.0523
	1757	8.5	30.5	22.60	.0522
	1918	10.9	28.5	24.10*	.0522
	2117	12.9	22.0	28.70	.0518
	2321	14.0	15.5	31.50	.0513
4/7/57	0341	18.3	11.5	33.40	.0500
	0934	24.2	7.1	32.80	.0518
	1257	27.5	5.3	31.10	.0500

* those readings which are most accurate due to release of gas just prior to reading

TABLE 8

RAW DATA

Sample: 50% Illite, 50% Sand
Sample Thickness at 0 Hours: 1.87 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.740
Void Ratio at 0 Hours: .734

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
3/30/57	0900	0.0	54	0.0	.099
	0915	.25	47	- .635	.100
	0930	.50	40.5	.762	.1008
	0945	.75	36.0	4.70	.100
	1000	1.0	36.5	——	.1003
	1025	1.4	36	7.25*	.101
	1053	1.9	35	8.13	.1011
	1200	3.0	34	10.92*	.103
	1235	3.6	33.5	14.22	.1039
	1330	4.5	31.5	16.50*	.1041
	1415	5.3	31.0	18.53	.1051
	1500	6.0	29.5	17.25*	.1057
	1900	10.0	21.5	27.2	.1057
	2353	14.9	10.6	27.4	.1054
3/31/57	0945	24.8	6.4	27.9	.1051
	1550	30.8	4.8	25.8	.1051
	1700	32.0	4.1	24.4*	.1048

* those readings which are most accurate due to release of gas just prior to reading

TABLE 9

RAW DATA

Sample: 40% Illite, 60% Sand
Sample Thickness at 0 Hours: 1.946 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.736
Void Ratio at 0 Hours: .630

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
4/2/57	1305	0.0	42	0.0	.0698
	1335	.5	36.5	1.52	.0702
	1405	1.0	28.5	5.08	.0703
	1440	1.6	28.5	9.65	.0725
	1550	2.8	28.0	9.54*	.0734
	1650	3.8	26.5	15.1	.0735
	1720	4.3	25.5	15.1 *	.0742
	2045	7.7	22.0	25.4	.0749
	2133	8.5	21.0	26.6	.0749
	2149	8.8	21.0	27.2	.075
	2245	9.7	20.0	25.9 *	.075
	2317	10.2	19.0	27.7 *	.0755
	2350	10.8	18.0	29.8	.0755
4/3/57	0838	19.5	7.3	29.4 *	.0748
	1056	21.8	6.9	29.0 *	.0757
	1408	25.0	6.0	30.5	.0759
	1500	25.9	5.7	29.2 *	.0761
	1747	28.7	4.8	28.3	.0761
	2003	30.9	3.9	27.8 *	.0740

* those readings which are most accurate due to release of gas just prior to reading

TABLE 10

RAW DATA

Sample: 30% Illite, 70% Sand
Sample Thickness at 0 Hours: 1.952
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.732
Void Ratio at 0 Hours: .508

Date	Time	Hours	Current MA	HT. of Rise-CM.	Comp. Dial Reading - In.
4/9/57	1310	0.0	40.5	0.0	.0662
	1340	.5	35.0	1.78	.0663
	1410	1.0	29.0	- 1.27	.0664
	1445	1.6	26.5	4.19	.0666
	1515	2.1	26.0	4.45	.0674
	1604	2.9	25.0	10.0	.0675
	1633	3.4	24.5	8.5	.0675
	1654	3.7	23.5	8.4*	.0676
	1740	4.5	22.5	11.9*	.0672
	1933	6.4	19.0	17.5	.0672
	2031	7.3	18.0	17.1*	.0672
	2115	8.1	17.5	18.9	.0672
	2200	8.8	17.0	18.4*	.0671
	2248	9.6	15.5	20.3	.0672
	2333	10.4	14.5	20.3*	.0671
4/10/57	0945	20.6	5.8	23.1*	.0663
	1115	22.1	5.5	23.9*	.0670
	1303	23.9	5.4	23.4	.0672
	1404	24.9	5.2	23.0*	.0677
	1502	25.9	5.0	22.0*	.0675
	1620	27.2	4.6	22.9	.0670
	1655	27.8	4.5	22.9	.0670
	1843	29.5	4.0	21.2	.0650
	1945	30.6	3.7	18.8*	.0652
	2053	31.7	3.4	18.8*	.0652
	2134	32.4	3.3	19.1	.0652
4/11/57	0925	44.3	1.5	16.5	.0643

* those readings which are most accurate due to release of gas just prior to reading

TABLE 11

RAW DATA

Sample: 20% Illite, 80% Sand
Sample Thickness at 0 Hours: 1.907 cm
Voltage Between Electrodes: 2.7 volts
Specific Gravity: 2.728
Void Ratio at 0 Hours: .525

Date	Time	Hours	Current Ma	HT. of Rise-CM.	Comp. Dial Reading - In.
4/13/57	0910	0.0	40.0	0.0	.0830
	0925	.25	35.0	0.0	.0830
	0940	.50	31.0	0.0	.0830
	0955	.75	27.5	0.0	.0830
	1010	1.0	24.5	0.0	.0830
	1040	1.5	22.0	- 1.27*	.0835
	1110	2.0	21.5	- 3.05*	.0836
	1140	2.5	20.5	0.0	.0838
	1210	3.0	19.0	0.0	.0838
	1310	4.0	17.5	0.0	.0837
	1410	5.0	15.5	0.0	.0836

* Readings taken just after release of gas. However, values returned almost instantly to 0.0.

APPENDIX B

SAMPLE COMPUTATIONS

SAMPLE COMPUTATIONS

Although the computations required for this thesis are relatively simple, an example of each is included herein so that there will be no question by the reader as to how certain results were obtained. All results are of slide rule accuracy.

Void Ratio

When the carbon disk was placed in the sample holder, a dial reading of .4628 was obtained. This reading was for a thickness of .372 in. The dial was so positioned that the reading decreased as the sample thickness increased. Consequently, to get the actual sample thickness it was only necessary to subtract the reading at any time from .4628 and add it directly to .372. Initial void ratio is based upon the samples as taken from the preloading tube being 1.995 cm thick which is the difference in thickness between the sample holder and the carbon disk plus one filter paper. The area of the preloading tube with a diameter of 2.5 in is 31.65 cm^2 while the inside area of the sample holder with a diameter of 2.505 in is 31.8 cm^2. This slight increase in area causes a reduction in thickness of sample from 1.995 cm to 1.985 cm for the same initial volume. Total original volume is 63.15 cm^3.

Example for 50% illite, 50% sand:

Weight of sample - 118.7 gm
Moisture Content - .261
Specific gravity - 2.74

$$W = W_s + W_w$$
$$= W_s + .261\ W_s$$
$$= 1.261\ W_s$$

$$W_s = \frac{118.7}{1.261} = 94 \text{ gm}$$

$$V_s = \frac{94}{2.74} = 34.3 \text{ cm}^3$$

$$V_v = 65.15 - 34.3 = 28.85 \text{ cm}^3$$

$$e_i = \frac{28.85}{34.3} = .842$$

At 0 hours or upon commencing the electrical treatment the volume of voids has decreased an amount equal to the difference in original thickness, 1.985 cm, and thickness at the given time, multiplied by the area, 31.8 cm^3.

$$V_v = 28.85 - (1.985 - 1.87)\ 31.8$$
$$= 28.85 - 3.66 = 25.19 \text{ cm}^3$$
$$e_o = \frac{25.19}{34.3} = .734$$

Void ratio for any other reading may be similarly computed.

Hydraulic Permeability

k is computed using the standard formula for a falling head permeameter.

$$k = \frac{a\ L}{A\ t} \ln \frac{ho}{hi}$$

where

a - area of tube (.4395 cm^2)
L - thickness of sample
A - cross sectional area of sample (31.8 cm^2)
h_o - elevation of water in tube above the constant level at start of test
h_1 - elevation of water in tube at any given time after start of test
t_1 - time in seconds between start of test and reading of head, h_1

Example for 50% illite, 50% sand:

$$k = \frac{.4395 \times 1.87}{31.8 \times 12.540} \ln \frac{27.4}{25.05}$$

$$k = .187 \times 10^{-6} \text{cm/sec}$$

Electro-osmotic Permeability

(a) Tangent method

Use the formula from THEORY and the tangent line from the plot of height of rise vs time curve. The tangent of the curve must be in the proper units of cm/sec; therefore, the actual plotted angle cannot be used.

$$k_e = \frac{F\ d}{0\ U} \tan\alpha_o$$

Example for 50% illite, 50% sand:

$$k_e = \frac{.4395 \times 1.87}{31.8 \times 2.7} \times \frac{40.5}{4.8 \times 3600}$$

$$k_e = 22.45 \times 10^{-6} \frac{\text{cm}^2}{\text{volt sec}}$$

(b) By formula at point of maximum rise

$$k_e = \frac{k_h\ h}{U} \frac{e^{\frac{kot}{Fd}}}{e^{\frac{kot}{Fd}} - 1}$$

Example for 50% illite, 50% sand

$$k_e = \frac{.187 \times 10^{-6} \times 29.3}{2.7} \frac{e^{\frac{.187 \times 10^{-6} \times 31.8 \times 75,600}{.4395 \times 1.852}}}{e^{\frac{.187 \times 10^{-6} \times 31.8 \times 75,600}{.4395 \times 1.852}} - 1}$$

$$= 2.03 \times 10^{-6} \frac{e^{.553}}{e^{.553} - 1} = 2.03 \times 10^{-6} \times \frac{1.738}{.738}$$

$$k_e = 4.78 \times 10^{-6} \frac{\text{cm}^2}{\text{volt sec}}$$

PART IX

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